Bulletin of the Geological Society of America

VOLUME 53 MARCH 1, 1942 NUMBER 3

CONTENTS

PAGES

Paleontology—an appraisal. By Lloyd W. Stephenson 373–380

Regional systematic jointing in slightly deformed sedimentary rocks. By John M. Parker, III 381–408

Phase petrology in the Cortlandt complex, New York. By S. James Shand 409–428

Correlation charts prepared by the Committee on Stratigraphy of the National Research Council, Carl O. Dunbar, *Chairman*

Introduction. By Carl O. Dunbar 429–434

Correlation of the outcropping Cretaceous formations of the Atlantic and Gulf Coastal Plain and trans-Pecos Texas. By Lloyd W. Stephenson, P. B. King, W. H. Monroe, and R. W. Imlay 435–448

Alkaline and carbonate intrusives near Bancroft, Ontario. By Felix Chayes 449–512

Subscription, $10 per year.

Publication Office: Florida Avenue and Eckington Place, Washington, D. C.

Communications for publication should be addressed to The Geological Society of America, Dr. H. R. Aldrich, Secretary, 419 West 117th Street, New York, N. Y.

NOTICE.—In accordance with the rules established by the Council, claims for non-receipt of the preceding number of the Bulletin must be sent to the Secretary of the Society within three months of the date of the receipt of this number in order to be filled gratis.

Entered as second-class matter in the Post-Office at Washington, D. C., under the Act of Congress of July 16, 1894.

Accepted for mailing at special rate of postage provided for in Section 1103, Act of October 3, 1917, authorized on July 8, 1918.

PRESS OF JUDD & DETWEILER, INC., WASHINGTON, D. C.

PAPERS IN PRESS FOR FORTHCOMING ISSUES

Geology in Public Works. By Charles P. Berkey.

Correlation Charts Prepared by the Committee on Stratigraphy of the National Research Council, Carl O. Dunbar, Chairman.

Correlation of the Silurian Formations of North America. By Charles K. Swartz, Chairman.

Résumé of Geology of South Permian Basin, Texas and New Mexico. By R. E. King and Others.

Amphibolites of the Lead Area, Northern Black Hills, South Dakota. By Theodore Dodge.

Ottawa-Bonnechere Graben and Lake Ontario Homocline. By G. Marshall Kay.

Stratigraphy and Structure of the Southern Ruby Mountains. By Robert P. Sharp.

Phosphorite Deposits on the Sea Floor off Southern California. By R. S. Dietz, K. O. Emery, and F. P. Shepard.

Spectroscopic Distribution of Minor Elements in Igneous Rocks from Jamestown, Colorado. By Joseph M. Bray.

Spitzenberg Conglomerate as a Triassic Outlier in Pennsylvania. By Lawrence Whitcomb.

Geomorphology of the Ventura Region, California. By William C. Putnam.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 53, PP. 373-380. MARCH 1, 1942

PALEONTOLOGY—AN APPRAISAL

BY LLOYD WILLIAM STEPHENSON

(Address as Retiring President of the Paleontological Society)

In a quarry high on the side of a mountain, far from the shore of any ocean, a workman sets his wedges in a mass of hard limestone; as the rock splits apart there is revealed the clean-cut imprint of a sea shell. At the foot of a high river bluff the eroding currents uncover the deeply buried bones of an animal, a beast unknown among living creatures of that vicinity. In the shale overlying a seam of coal a miner finds the beautifully preserved imprints of fern leaves and the stumps and trunks of strange extinct trees. Astonishing discoveries these, it seems; but really commonplace to those who specialize in the study of such things. The things discovered are the fossil remains of animals and plants that lived in past geologic periods.

Fossils, sports or freaks of nature they were sometimes called before their true nature was understood. Paleontologists searching the outcropping rocks for fossil remains are frequently asked by local people, "What good are fossils?" The question is a fair one for, as often as not, the asker is a member of the tax-paying public—a farmer, a merchant, the owner of a quarry. In the aggregate, important amounts of public money are spent each year to provide for the study of fossils.

Paleontology, the science that treats of fossils. "What good is paleontology?" To a questioner unschooled in the fundamental facts of biology, and handicapped by a heritage of erroneous dogma, an attempt to give a satisfying answer is a futile waste of words; he is not qualified to understand.

To the practical man of business affairs, in whose mind the mercenary point of view is always uppermost, who sees good only in those things that bring pecuniary reward, paleontology, as a *pure science*, is indeed a foolish waste of time, thought, and money. But the science of paleontology has demonstrated its ability to function well in fields outside the realm of pure science. In the Gulf Coast country, as an oil-prospecting well penetrates deeper and deeper into the earth, the prospector wants to know, "Does this or that narrowly restricted fossil zone run high or low?" If high, the prospects are good that the well is favorably located above a positive structure, and he knows about how far it will be necessary to drill to reach

the expected oil-bearing sand. On the other hand, if the fossil zone runs low, another duster may soon be added to the ever-mounting list of unsuccessful ventures. Knowledge of restricted fossil zones and a clear understanding of the age and stratigraphic relations of the sediments making up the section in a region where hidden oil-bearing structures challenge discovery are now considered essential to successful oil prospecting. This information paleontologists alone are qualified to furnish. They alone have the training necessary to enable them to differentiate structure-determining zones and to identify the fossils characteristic of each such zone. Who can imagine a more practical assortment of human brains than that represented by the executive staffs of the major oil companies? Yet these men are willing to pay, and do pay, for the information. In exceptional cases they have paid at rates as high as $35,000 or more a year for the services of paleontologists.

What has been said of the relation of paleontology to the petroleum industry is true also with respect to other mining industries, though perhaps in a less spectacular way. A knowledge of the stratigraphic position of mineral resources that occur in sedimentary formations is now accepted as necessary by the officials of most of the larger operating companies. Clay, sand, gravel, coal, manganese, phosphate, bauxite, potash, iron ore, and placer gold are some of the mineral products that fall in this category.

Geologic maps are of fundamental importance in the development of mineral resources. For more than 100 years, geologists, including paleontologists, sponsored by museums, universities, and official State and Federal Surveys, have been mapping in greater and greater detail the geologic formations that appear at the earth's surface. From time to time, geologic maps of North America, of the United States, and of the several States are issued. Each serves its purpose for a while but, as more detailed information is accumulated, each becomes more and more outdated, and less and less useful, and revised maps must be compiled and issued. It would be difficult accurately to evaluate the part played by paleontology in the preparation of these maps. Each map bears a legend that purports to classify the formations shown thereon with respect to geologic eras, periods, and epochs. It is only by the use of fossils that this classification is successfully accomplished. Unless limited by formations of known age both below and above, the age of a nonfossiliferous sedimentary formation cannot accurately be determined.

From the utilitarian standpoint, the science of paleontology has proved its worth. It has earned its present place in the curricula of our schools and in our national economy.

The worth of paleontology is not confined to its utilitarian aspects, however; the science has educational and cultural value. To the man or woman who sees in life something more than material gain, who seeks soul satisfaction in the attainment of knowledge and the discovery of truth, the fossil record of past life on the earth is an eminently worthwhile subject of research. "Speak to the earth and it shall teach thee." (Job, chapter 12, verse 8.) And again, "Ye shall know the truth, and the truth shall make you free." (John, Chap. 8, verse 32.)

Paleontology is history in the broadest meaning of that term. It is history unaffected by the personal bias of the historian; for in this case the historian is Nature herself. Aptly it has been said that history beyond the reach of folklore is written in the rocks. To the extent that the living things of the past have been preserved in fossil form the record is true and reliable. Every fossil, properly labeled as to locality and geologic position, and correctly identified, adds its bit to the constantly mounting volume of information about the history of the earth and its inhabitants.

Some of the modern biologists classify living animal organisms into twelve major divisions, each of which is called a *phylum*. Three of these phyla include only soft-bodied creatures that are never found preserved as fossils. The remaining nine phyla have left records of themselves in the rocks. None of the records is complete; some are only fragmentary.

The record of the *origin* of life is lost in the obscurity of the past. Probably more than the first half of the history of life is blank, owing to the total absence of fossils. Paleontologists can scarcely hope to contribute anything toward the solution of the problem of life's beginning. Authentic evidences of life in rocks older than the Cambrian period, some 500,000,000 years ago, are limited to the simple plant organisms known as calcareous algae, to wormlike borings, to some questionably identified sponge spicules, and to a few other remains of dubious character. The algae are abundant; the others as known are meager.

Why did our historian fail to give us a record of life in its earlier stages? Because, some say, not until the beginning of Cambrian time did animal organisms develop hard parts that could readily be preserved as fossils. But it does not seem reasonable that hard parts should have been developed simultaneously in at least eight phyla of animals. The enigma is not lessened when it is remembered that a great system of pre-Cambrian rocks, in which traces of life other than calcareous algae are meager, includes vast thicknesses of sedimentary rocks many of which seem not to have been so drastically changed as to effect wholesale destruction of contained fossil remains, particularly if the organisms had possessed hard parts.

Here then is a wide field for paleontologic research. Judging from past results, it is not a fertile field, but it is an alluring one. It is a field for the efforts of present or future paleontologists possessed of much patience and keen powers of observation. To them, we hope, will go the credit for giving us at least some chapters in the story of life in its earlier stages.

Second only to the mystery of life's origin is the enigma of the sudden appearance in rocks of early Cambrian time of abundant fossil remains; all but one of the nine phyla of animal organisms known in the fossil state are represented. By means of these fossils the broader trends in the evolutionary development of the organisms can be traced down through 500,000,000 years of time, even to the present. The history of the ninth phylum, the vertebrates, begins with fishes in the Ordovician, the period next younger than the Cambrian, and is recorded in the rocks through the succeeding ages, to the fishes, amphibians, reptiles, and mammals of the present day.

If then we would know the story of living organisms as fully as it is possible to know it, we must turn to paleontology. In Nature's great history book much of the story is recorded. Fossiliferous layers of sand and sandstone, clay and shale, marl, limestone, and chalk are the pages of this great book. The book is in sections, scattered here and there over the face of the earth—in the Paris Basin, on the southern shores of England, in the high plateaus of Asia, in the deserts of Africa, in the Black and Grand Prairies of Texas, in the hills of New York, and at thousands of other places from the highest mountains down to and even below the level of the sea. Each section has furnished its quota of the sum total of the story of life as we now know it. We have made a good start in our attempt to read this story, but only a start, for many pages have not been turned, and many have been only partly turned. It is as if, in reading a book, we would turn back only the corners of some of the pages, revealing a few words and parts of a few lines. Hints of the contents of the book are gained, but only by turning the pages all the way back is the full story revealed. Much of our work in paleontology heretofore has been mere corner turning. The good earth still holds vast undiscovered treasures of fossil plants and animals that await the painstaking efforts of devoted, truth-seeking students.

Human history is generally thought of as having begun in an obscure sort of way, with the earliest known human or humanlike remains dating back a million years or so. The history has become progressively clearer and more authentic through the evidence afforded by the relics of the Stone Age, the skeletons of later human races, the ancient murals on the walls of European caverns, the hieroglyphics on tablets of clay and stone, and, finally, by the written and printed records of the more recent

centuries. But these records do not furnish a satisfactory explanation of the real origin of man, nor of the manner of his creation. Why limit our historical research of man to that part of geologic time which sees him as a fully developed human animal? Why omit the fascinating story of his evolutionary development from its beginning in a simple one-celled organism, blindly pulsating and persistently reproducing its kind in some primordial sea, down through vast eras of time to his present exalted place as the intellectual superior of all other creatures of the earth?

Here again is a project for the paleontologist, a project worthy of his best efforts. Already Osborn, Gregory, Simpson, and many others have given us glimpses of our primate ancestry far back into the Tertiary period; but the complete connected story is yet to be told, and scarcely anything is known of our still more ancient ancestry, back through the primitive mammals of the Cretaceous and Jurassic periods, still farther back through the reptiles of the Triassic, the amphibians of the Carboniferous, the fishes of the Devonian, Silurian, and Ordovician, and in some dim and mystic pre-Cambrian era to an original one-celled organism. What particular genera and species of primitive mammals, of reptiles, of amphibians, of fish, make up man's ancient pre-primate lineage? With apologies to the poetess, Florence Percy, "Backward turn backward, O Time in your flight, make me a"—fish again, just for tonight.

To the fundamentalist who sees man suddenly created by the grace of God, manufactured outright from the dust of the earth, a creature totally unrelated to all his fellow creatures, this conception of creation by an interminably long line of evolutionary processes must indeed seem an impossible and shocking one. To him the thought of blood relationship to the slimy, grovelling creatures that make up the trunk and earlier branches of his ancestral tree is unthinkable. On the other hand the biologist finds in evolution an awe-inspiring method of creation; he sees in the nervous reflexes of the original one-celled parent the nuclear beginnings of intellect and soul; he is amazed that the tragic struggle of his early lowly ancestors blindly following some inner urge step by step from lower to higher stages could have led finally to the creation of a being having the mental and spiritual attributes of man.

We must look to the organic chemist, the physiologist, the biologist, and the experimental breeder for discoveries that reveal the actual processes by which the evolution of organisms is accomplished. Once the possibility of evolution is established, it becomes the duty and privilege of paleontologists to seek out the confirmatory evidence of evolution afforded by fossils and to construct the ancestral trees of the various races of animal and plant organisms, including the human race.

Each paleontologist is a translator of some paragraph, some section, some chapter in Nature's great history book. He divides geologic time into eras, periods, and epochs; he determines the geologic ages of the sedimentary rocks and the relative ages of these rocks in different parts of the earth; he traces the shore lines of the ever-changing continents of the geologic past; he unravels complicated faulted and folded rock structures in the hills and mountains; he identifies, names, and lists the kinds of plants and animals that inhabited the earth during each time division; he traces the lines of descent of organisms from their first appearance in the rocks to their later extinction, or to their representatives in living floras and faunas. In short, he provides an essential part of the data wherewith to reconstruct the moving drama of earth events during the long eons of time before the earliest human recordings.

Such a reconstruction furnishes a background for a clearer understanding of both the recorded events of late historic times and of the strange and tragic doings in our present troubled world. Through some hundreds of millions of years of our evolutionary development the unwritten law that "might makes right" was, in the very nature of the case, an effective, yes an essential, law in determining who would eat and who would starve, who would have shelter from the cold and who would suffer or perish in the wintry blasts, and who would occupy the places of advantage and control among their competing fellows. It was not until the brains of our savage ancestors reached a state of development approaching that of *Homo sapiens* that justice, fair play, and the Golden Rule could begin to exercise effective control over the activities and conduct of the race. It was only then that laws intended to protect the rights of individuals could be formulated.

As the geologist reckons time, these ideas are very recent influences in animal conduct. They seem still to be in an experimental stage. The old philosophy that "to the victor belong the spoils" is not dead. It has a powerful backing in Naziism, which is an unhappy flareback to the self interest that governed the conduct of our struggling savage ancestors. It is clearly manifest in the treacherous and merciless aggression so persistently engaged in by the military clique of Japan. It is not dead even among the nations whose people are now pouring out their lifeblood to quench the consuming flame of these pagan philosophies. Utopia is still far away. How many of the nations now struggling to stop this onrush of aggression have clean records in their past dealings with their weaker neighbors? How many more world wars will it take to prove that the hope of the human race lies not in a philosophy of individual or national selfishness, but rather that it lies in that opposing philosophy which is built upon a foundation of unselfish consideration

for the rights of others, of mutual helpfulness among individuals and nations, a philosophy that teaches the stupidity of destructive wars, and the world-wide benefit of constructive peace?

If man's *physical body* was created by the process of evolution, it seems inescapable that his *intellect,* which springs from his physical brain, and that intangible something called *soul,* which is inseparably connected with his intellect, were simultaneously developed in intimate association with his physical body. The paleontologist, viewing the human race in the light of the evolutionary development of organisms in general, sees man now in an incomplete stage of racial growth. He sees as the best product of man's evolutionary growth at the present stage those higher intellectual and spiritual attributes to which I have previously referred—unselfishness, recognition of the rights of others, obedience to the Golden Rule. He concludes that, unless man has already passed the zenith of his development and is on the downgrade to extinction, he must rise still higher. He must reach a stage in which reason will supplant force. Eschewing the disgusting brutalities of total war, individuals, races, and nations will settle their differences on the basis of justice and fair play.

To summarize, the benefits of the science of paleontology fall into two major categories. (1) Utilitarian—To those who devote themselves to developing the mineral resources of the earth for the satisfaction of human needs, the science has proved its worth; it is essential in determining the geologic age and the stratigraphic position of these resources, and it is useful in the more practical business of determining the actual position in the ground of minerals in given prospects; it plays a leading part in the preparation of geologic maps. (2) Educational and cultural—Paleontology as a pure science furnishes data that are necessary in interpreting the sequence of events during some hundreds of millions of years of earth history; it presents confirmatory evidence of the evolutionary development of existing complex organisms, including man, from original, simple, one-celled progenitors; it provides a background for a clearer understanding of the complex, and often conflicting, interrelationships of individual, national, and international affairs; and, finally, it furnishes a basis for an optimistic outlook on the future development of the human race, an outlook that sees man's evolutionary trend carrying him above the destructive cruelties, hatreds, and brutalities of war, to the lasting ways of peace made possible by the exercise of reason and the recognition of the rights of all men.

U. S. Geological Survey, Washington, D. C.
Manuscript received by the Secretary of the Society, December 20, 1941.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 53, PP. 381-408, 4 PLS., 6 FIGS. MARCH 1, 1942

REGIONAL SYSTEMATIC JOINTING IN SLIGHTLY DEFORMED SEDIMENTARY ROCKS

JOHN M. PARKER, III

CONTENTS

	Page
Abstract	382
Introduction	382
General statement	382
Acknowledgments	383
Field methods	383
Pattern of joint sets	384
Treatment of data	384
Local constancy of joint pattern	385
Regional swing of joint pattern	387
Relationship of joint sets to other structures	388
Folds	388
Faults	391
Regional dip	391
Age of joints	392
General consideration	392
Folding	392
Faulting	393
Warping	394
Dike intrusion	394
Characteristics of the fractures	395
General considerations	395
Set I	395
Set II	396
Set III	397
Cause of jointing	398
Character of Appalachian stresses	398
Shear joints of Set I	398
Theoretical analysis	398
Experimental work	403
Tension joints of Set II	406
Doubtful joints of Set III	406
Summary	406
References cited	407

ILLUSTRATIONS

Figure	Page
1. Map of the Owego, N. Y. quadrangle showing the strikes of the joint sets	386
2. Map of the regional structural location of joints in parts of New York and Pennsylvania	390

Figure Page
3. Resolution of stresses 400
4. Relative values of stress components 401
5. Relative values of stress components at varying angles of shear 402
6. Relative values of stress components at varying angles of shear 404

Plate Facing page
1. Joints in homogeneous rocks 394
2. Joints in nonhomogeneous rocks 396
3. Joint surfaces and test specimens 397
4. Map of parts of New York and Pennsylvania showing strikes of joint sets 408

ABSTRACT

Data on more than 6000 joints cutting the nearly horizontal Paleozoic strata of east, central, and southern New York and northern Pennsylvania reveal three contrasting regional sets. The local consistency of the joint pattern and a gradual regional swing are established. The lack of consistent relationships of the joints to other structures, especially the tracing of a "dip" set across the area into the "strike" position, indicates that the joints formed independently of, and earlier than, the folds, faults, and regional dip. The principal set consists of two conjugate shears intersecting at very acute angles (averaging 19°); its pattern is radiating for the whole area. Theoretical analysis, confirmed by experimental tests, points to an origin by shearing under simultaneous compression and tension acting at right angles. The second set is single and lies about perpendicular to the first, thus forming a pattern of concentric arcs; it originated from tension. These two sets constitute a system of practically contemporaneous fractures. The minor set mantains a constant position for the entire area; it probably is tensional but originated under doubtful circumstances, perhaps at a different time.

INTRODUCTION

GENERAL STATEMENT

The systematic jointing of central New York has been well known in the geologic literature since the early report of James Hall in 1843, and since then it has frequently been referred to and investigated. Sheldon (1912) in particular helped clarify the character of the jointing and its relationship to other structures at certain localities. However, similar work covering large areas has been lacking, and, furthermore, a notable lack of agreement as to the mechanics of formation of these fractures has existed.

This study was undertaken to formulate an adequate theory of the origin of systematic jointing on a regional scale in slightly deformed sedimentary rocks. First the pattern of the joint sets in a small area and its degree of constancy were determined. Then changes in this pattern over a larger area were traced, and the relationship of the jointing to other tectonic structures studied. After the pattern and characteristics of the joints were established, a combination of stresses capable of producing such fractures was postulated, and the theory tested experimentally.

The area studied covers 24 quadrangles lying in eastern, central, and southern New York and northern Pennsylvania (Pl. 4). It is a portion of the glaciated Allegheny Plateau, with gently rolling uplands lying 500 to 800 feet above the steep-sided, flat-bottomed main valleys. Good exposures abound where the smaller tributary streams have cut deep gorges into the plateau. The remarkably regular jointing and the even stratification give the ravine walls a strikingly architectural appearance, heightened by the stairlike form of cascades.

The rocks range from upper Ordovician at the northern edge to upper Devonian at the Pennsylvania line. Most data came from the middle and upper Devonian Hamilton, Portage, and Chemung formations. These are firmly compacted brittle shales interbedded with fine-grained tough sandstones in lenticular layers ranging in thickness from less than an inch to about 2 feet. The proportion of sandstone ranges from less than 10 per cent in the Hamilton to nearly 50 per cent in the Chemung. These formations are only slightly deformed, irregular low folds interrupting a gentle regional dip.

The work was commenced in the summer of 1934 and was presented the following year in a doctor's thesis at Cornell University. The area studied was much extended and the conclusions modified by 2 months field work during the summer of 1938. Experimental work was carried on mainly at North Carolina State College during the winter of 1937-1938.

ACKNOWLEDGMENTS

The writer gratefully acknowledges his indebtedness to the members of the Department of Geology at Cornell University for information and advice, and for the assistance of the Eleanor Tatum Long Scholarship during 1934-1935. The author is especially grateful to Prof. C. M. Nevin, under whose supervision the work was done. The influence of Dr. Pearl Sheldon's earlier work has been considerable and personal conference was of further aid. Dr. J. F. Pepper generously allowed the use of his data on the joints in the Hudson River region. The experimental work was made possible by Prof. A. E. Wells of the Sibley School of Engineering at Cornell University and by Prof. Harry Tucker, Director of the Engineering Experiment Station of the North Carolina State College of Agriculture and Engineering. Professors James Fontaine and H. B. Shaw contributed to the designing of experimental apparatus.

FIELD METHODS

Great numbers and varieties of fractures break the nearly flat rocks into comparatively small blocks. Only rarely are the joints spaced as

much as a yard apart. This multiplicity necessitated discrimination in taking data; the many irregular breaks without consistent orientation were avoided. In the smaller exposures the strikes of all the longer, straighter, and more consistent joints were determined with a Brunton compass. In extensive exposures the same procedure was followed in a selected portion of the outcrop, with a few readings added from the other parts as a check. The data recorded are thus roughly proportional to the number of good joints in an outcrop. The majority of the joints are vertical, but where the hade was noticeable (2-3°), it was also measured. The character and relationships of the joints, the lithology and orientation of the outcrop, and the presence of other structures were also noted. Depending on the size and character of the exposure, the number of joints measured at each station varied from about a dozen to well over a hundred, averaging about 30. The total for each quadrangle varied from about 100 to nearly 800. The number of stations per quadrangle varied from 5 to 21. Altogether 5490 joints were measured at 177 stations. An additional 1308 readings of joint strikes in four quadrangles in eastern New York (Albany, Coxsackie, Catskill, and Rhinebeck) were obtained from Dr. J. F. Pepper.

PATTERN OF JOINT SETS

TREATMENT OF DATA

Though superficial observation indicates that the joints are grouped together in sets of approximately parallel strike, sufficient variation exists within each set so that statistical methods are needed to give the averages. The joint strikes measured in each unit area were tabulated into azimuth groups having a 5-degree range. The mid-points of these groups were north and every 5-degree azimuth to east and west, the groups thus ranging, for example, from N. 2½° W. to N. 2½° E. and from N. 2½° E. to N. 7½° E. In preparing Figure 1, tabulations were made for each station, and in Plate 4, for each U. S. Geological Survey 15-minute quadrangle.

In constructing the diagrams for Figure 1, the average strike of each set was determined by calculating from the tabulations the weighted arithmetic mean. The percentage of the total number of joints at the station belonging to each joint set was then computed. Only rarely were the strikes so divergent and poorly concentrated that the boundaries of the sets were doubtful. Each line of the diagrams is a vector whose direction shows the mean strike of the set and whose length is proportional to the percentage of joints in that set. The number of

joints per station varies from 15 to 133, and the total for the quadrangle is 765.

In Plate 4 the diagrams were constructed on polar co-ordinate paper and later transferred to the map. Distances proportional to the number of joints in each 5-degree group were laid off on each side of the center, in the directions of the mid-points of the group. These points, varying in distance from the center, were then connected in proper sequence by straight lines, except that where a group was not represented the line was brought back to the center. In order to keep the diagrams of similar size in spite of varying number of data different scales were used, the radius of the circle representing 10 joints. The data for the four quadrangles along the eastern side of the map (Pl. 4) came exclusively from the relatively undisturbed Devonian formations which outcrop along the western edges of the areas; in all other cases the diagrams are representative of the whole quadrangle.

LOCAL CONSTANCY OF JOINT PATTERN

Figure 1 shows the joint pattern at 20 stations in the Owego quadrangle, New York, an area roughly 13 by 17 miles. At all stations two sets of joints are apparent, and at some a third is present. In nearly every instance the north-northwest set (called Set I) dominates numerically. Its direction is the most consistent, the strike varying in steady progression from N. 14° W. at the eastern edge of the quadrangle to N. 24° W. on the west. These "master joints" are the most planar and vertical. This set is unusual in being double, that is, the joint strikes cluster at two directions averaging 16° apart, with few intermediate joints. Most of the fractures of this set follow one of these two directions (in this case the more westerly one) rather than being equally divided. Frequently, however, two fractures of identical character intersect at acute angles (Pl. 1, fig. 1). In several exposures a single fracture was observed to bend sharply from one direction to the other. Sometimes the fractures in one layer belong to one component and those in the adjacent layer to the other.

The second most important set (Set II) trends about east-west, but varies considerably and with little regularity. While the extreme range is from N. 70° E. to S. 70° E. this set in most cases lies within 10° of east-west. The fractures are irregular, rough, and curving but are often more extensive than the master joints (Pl. 2, fig. 3).

A third set of straight, vertical joints (Set III), having a nearly constant strike of N. 60° E., appears in places. Although poorly represented in this quadrangle, they become prominent in neighboring ones (Apalachin and Ithaca).

Similar results have been obtained by Sheldon (1912) from a more intensive study of a smaller area (8 by 12 miles) near Ithaca. The double "dip" set described by her corresponds to Set I, the single "strike"

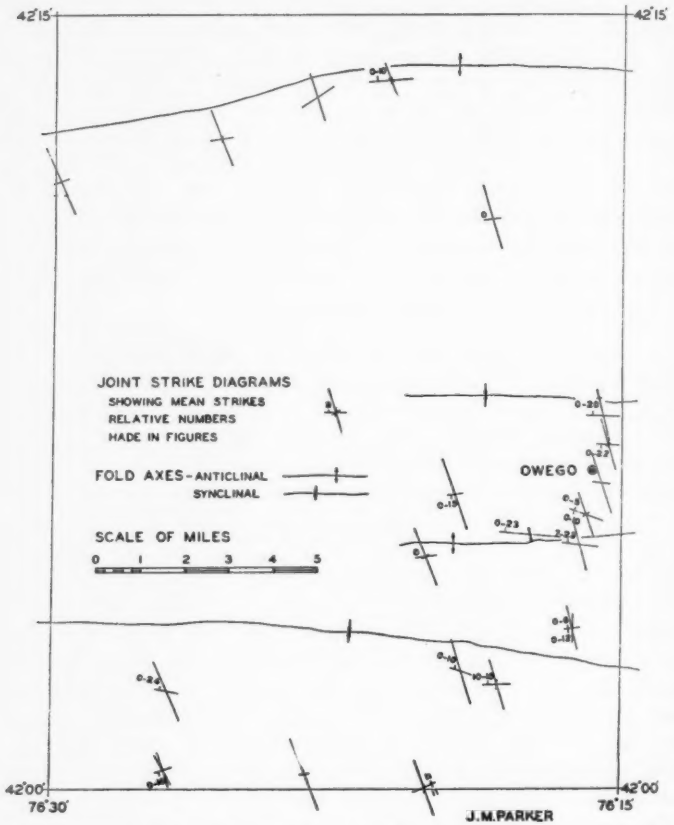


FIGURE 1.—*Map of the Owego, N. Y., quadrangle showing the strikes of joint sets*

set to Set III, and the minor joints to Set II. The relative abundance of the two sets lying near the strike of the strata (Sets II and III) is reversed in these two areas. Set III is exceptionally developed near Ithaca, but in most of the areas studied is decidedly subordinate. In other respects the results of studies in these two small areas agree completely.

REGIONAL SWING OF JOINT PATTERN

Since the joints are not only systematic at each outcrop but also consistent for small areas, the major sets at least may be traced from one locality to another and changes in trend over a large region detected.

TABLE 1.—*Mean strikes of joint sets and angles between them*

Quadrangle	Set I				Set II	Set III	Angle between median of Set I and Set II (degrees)
	West component	East component	Median direction	Angle between components (degrees)			
Albany	N 2° E	N 25° E	N 14° E	23	N 45° W ?	N 55° E	59 ?
Coxsackie	N 15° E	N 33° E	N 24° E	18	N 70° W	N 67° E ?	94
Catskill	N 11° E	N 25° E	N 18° E	14	N 75° W	N 45° E ?	93
Rhinebeck	N 10° E	N 25° E ?	N 18° E ?	15 ?	N 71° W		89
Berne	N 5° E	N 30° E	N 17° E	25	N 67° W	N 65° E	84
Durham	N 2° W	N 28° E	N 13° E	30	N 50° W ?	N 57° E	63 ?
Schoharie		N 25° E			N 85° W	N 60° E	
Richmondville	N–S				N 55° W ?	N 50° E	
Richfield Springs	N 3° W	N 13° E	N 5° E	16	N 85° E	N 55° E	100
Cooperstown	N 5° E	N 18° E	N 11° E	13	N 86° E	N 62° E	105
Andes	N 10° W	N 5° E	N 2° W	15	N 88° E	N 55° E	90
Winfield	N 5° W	N 16° E	N 5° E	21	N 77° E	N 52° E	108
Oneonta		N 10° E			N 80° W	N 52° E	
Unadilla	N 2° E	N 22° E	N 12° E	20	N 82° W	N 51° E	94
Oxford	N 5° E	N 20° E	N 12° E	15	N 71° W	N 65° E	83
Binghamton	N 7° W	N 10° E	N 2° E	17	N 78° W	N 65° E	80
Apalachin	N 13° W	N 5° E	N 4° W	18	N 87° E	N 64° E	89
Dryden	N 17° W	N 5° E ?	N 6° W ?	22 ?	N 85° W	N 65° E	79 ?
Owego	N 18° W	N 2° W	N 10° W	16	E–W	N 60° E	80
Towanda	N 21° W	N–S	N 10° W	21	N 84° E		86
Ithaca	N 23° W	N 3° E	N 10° W	26	E–W	N 67° E	80
Waverly	N 28° W	N 15° W ?	N 21° W ?	13 ?	N 78° E		81 ?
Sayre	N 30° W	N 11° W	N 20° W	19	N 80° E	N 60° E	80
Elmira	N 35° W	N 18° W	N 26° W	17	N 70° E		84
AVERAGES				19		N 59° E	86

In Plate 4 the average strikes of the joints in 24 quadrangles are shown. The joint pattern exhibits considerable variety in different quadrangles, as the relative prominence of the sets changes and confusing local sets appear. Nevertheless, a fundamental unity is apparent, best shown where the most data were obtained, as in the Coxsackie, Dryden, Owego, and Richfield Springs quadrangles.

The fundamental pattern of this larger area is the same as that of the Owego quadrangle. Table 1 gives the mean directions of the three sets for each quadrangle and the angles between them. The angle in

the last column was measured from the median direction of Set I counterclockwise to Set II. The position of some sets in certain quadrangles is not apparent from the diagrams (Pl. 4) but has been supplied in the table from the field notes where possible. In the diagrams roman numerals identify the three main sets.

The principal set (Set I) is double, the angle between components averaging 19°, though ranging from 10° to 30°. This set has a radial plan, the mean direction progressively swinging in strike from about N. 20° E. on the east to N. 25° W. on the west. This swing was noted in the western portion of the area by Wedel (1932) and by Bradley and Pepper (1938) and was shown to continue at least three quadrangles farther west.

Set II shows less consistent changes in strike, though in general it lies about perpendicular to the master joints. Its average position is 86° west of the median of Set I; in only four quadrangles does it lie more than 11° from the right angle position, with the acute angle usually to the northwest. Conforming with Set I's radial plan, this set forms concentric arcs for the area as a whole, striking about N. 70° W. on the east, east-west in the center, and N. 70° E. on the west.

Set III shows a remarkably constant strike across the whole area, averaging N. 59° E. In only one quadrangle (Catskill) does this set vary more than 9° from this average strike. In certain quadrangles (Albany, Ithaca, Richmondville) this set attains a prominence equalling or even exceeding that of Set I. In neighboring areas, however, it may be poorly represented, and in four quadrangles it was not recognized.

Since the radiating Set I and the concentric Set II pass through comparable changes in trend, of which Set III is independent, the fundamental joint system of this area appears to consist of a master set of two acutely intersecting components with a subordinate single set lying at right angles. A notably similar joint pattern has been described by Melton (1929) in central and eastern Oklahoma, where the joint strikes are arranged radially and in concentric arcs with respect to the curved zone of faulting and folding of the Oauchita Mountains.

RELATIONSHIP OF JOINT SETS TO OTHER STRUCTURES

FOLDS

In determining the stresses responsible for the jointing, the type, orientation, and possible relationship of other tectonic structures in the area,—such as folds, faults, and regional dip—should be considered.

In the eastern part of the area the strata have been folded and tilted westward. The Hudson River region has been subjected to both the Taconic and Appalachian orogenies, but only the effects of the latter

are relevant, as the joint data came from the gently dipping Devonian formations. According to Pepper (1934, p. 186) the Appalachian folds trend N. 10° E. between Kingston and Albany. However, "wherever well developed, the cleavage almost invariably had a trend of N. 25-30° E.", which "trend corresponds exactly to that of the Appalachian folding farther south" (Pl. 4).

In the western half of the area is a series of low, irregular anticlines and synclines, that plunge mainly southwestward and die out to the east. Dips of more than 3° are rare; the south limbs of the anticlines are usually steeper. The positions of the axes as shown in Plate 4 and Figures 1 and 2 are taken from Wedel (1932), Bradley and Pepper (1938), Cathcart (1934) and U. S. Geological Survey (1932). These sinuous fold axes run nearly due west until near Long. 77° they turn to the southwest. This curve, continuing in the area further south and west, corresponds to the great salient of the closely folded Appalachians in central Pennsylvania.

In the Hudson River region Set I nearly parallels the folds and constitutes the "strike" set. In central New York this same set lies perpendicular to the fold axes, in the "dip" position. Its regular progression from "strike" to "dip" position indicates a regional independence of folding.

In south-central New York Wedel (1932, p. 30) noted that the gradual swing in strike of the "dip" joints corresponded roughly to the bend of the fold axes. However, as pointed out by Bradley and Pepper (1938, p. 30), the joints are independent of local variations in the individual folds.

In Figure 2 the mean strikes of the joint sets, as given in Table 1, have been plotted, the longest lines representing Set I, the intermediate lines Set II and the shortest Set III. The regional dip in the Allegheny Plateau and the positions of prominent folds and thrust faults in the Appalachian Mountain and Piedmont provinces are also shown. The strikes of the master joints (if projected) converge toward the Piedmont area of southeastern Pennsylvania. The Appalachian folds swing around this area in a great salient concave to the southeast and continue into southeastern New York with a reverse curve to the north-northeast. While the Set I joints in south-central New York apparently conform to the southwest end of this double S-curve, those farther east do not change comparably as the folds swing north, but converge toward the same general area. Thus, "dip" joints become "strike" joints, indicating that Set I is not a consequence of the folding, though it may have resulted from the same stresses which caused the folds.

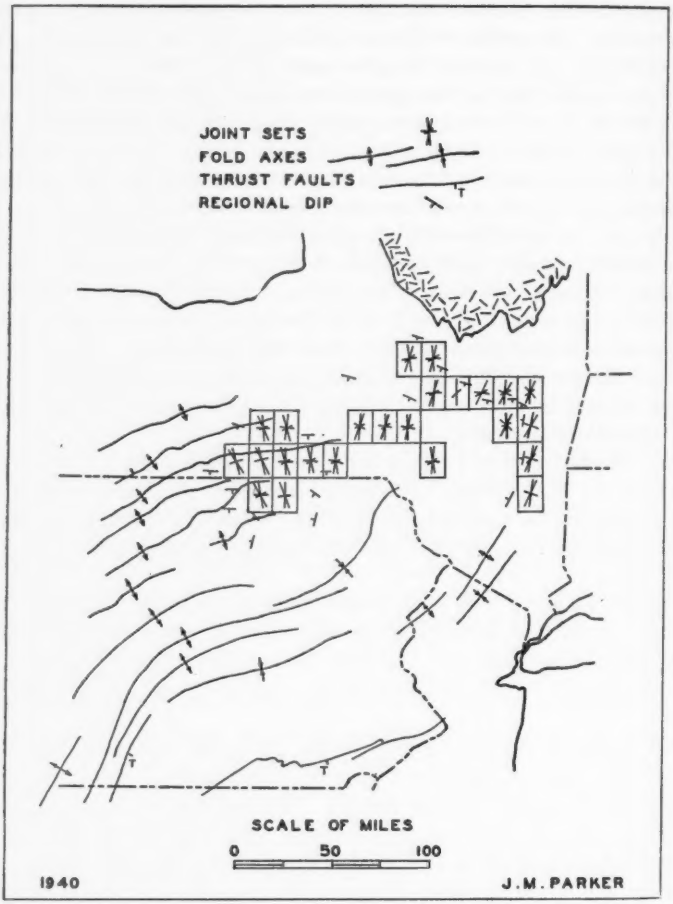


FIGURE 2.—*Map of the regional structural location of joints in parts of New York and Pennsylvania*

The less regular Set II exhibits a pattern of concentric arcs for the whole area, thus occupying the "dip" position in eastern New York and the "strike" position farther west. This, together with its fixed position nearly at right angles to the median of Set I, indicates that Set II is also independent of the folds. Though the frequently close parallelism between Set II and the fold axes (Pl. 4) suggests a possible genetic

relation, the greater detail of Figure 1 points to a contrary conclusion, since occasional lack of parallelism can be noted. Further, the hades of these joints do not agree with this origin; if formed by bending of arches, the joints on opposite flanks should converge downward, whereas actually they show no consistent relation. The hade of the joints is generally much more (up to 24°) than the dip of the strata, which in this quadrangle nowhere exceeds 3°. These joints may also hade in both directions at one outcrop. They appear to be no more numerous near fold axes than between. The form of the folds is best known near the western margin of the area. Bradley and Pepper (1938, p. 29) have shown them to be elongated domes and basins of irregular shape and haphazard arrangement. Their notable lack of system makes it seem unlikely that they were responsible for the systematic jointing.

Since Set III has a nearly constant strike everywhere, while the eastern folds lie nearly perpendicular to the western ones, there is apparently a complete lack of genetic connection here also.

FAULTS

A few thrust faults, mostly with very small displacements, occur, especially in the Hudson River region, in south-central New York, and northern Pennsylvania. Detailed descriptions are given by Cathcart (1934), Robinson, *et al.* (1932), Ruedeman (1930), Sheldon (1912; 1927; 1928) and Wedel (1932). Most of these faults, closely related to specific folds, are interpreted as resulting from a continuance of the folding stresses. Consequently, they are as unrelated to the jointing as is the folding. Further, the limited extents and displacements of these faults indicate that they could hardly have been responsible for uniform jointing over so large an area. Disturbed jointing near some of the faults, and definite offset of joints by other faults, proves the jointing in these cases to be older than the faulting.

REGIONAL DIP

The dip symbols on Plate 4 and Figure 2 give the regional dip of the surface formations. In the western portion of the area, the directions were taken from a map by Sherrill (1934). The rest were calculated from the positions and elevations of formation contacts. The dip is low, averaging about 40 feet per mile, but in places may be four or five times as much (nearly 2°). The area studied lies at the northeast end of the Pittsburg-Huntington Basin, a great structural trough which plunges about S. 60° W. toward the southwest corner of Pennsylvania. The strata dip west and west-northwest along the eastern side, and southwest or south over the rest of the area.

While throughout much of this territory the terms "strike joints" and "dip joints" are appropriately applied, the joints are independent of the regional dip. In the northeastern quadrangles the formational dips swing through a right angle while the joint directions remain unaffected. From the east to the west margin the strata change in strike over 100°, while Sets I and II change about 45° and Set III stays constant.

This regional dip of the surface rocks, however, is a composite result of several earth movements: the subsidence of the geosyncline during deposition, the late Paleozoic orogeny, and the more recent Mesozoic and Cenozoic uplifts. Since the joints developed in consolidated sediments and earlier than the folding, the only movements pertinent to the present problem are those of the early stages of the orogeny. These cannot be adequately evaluated, because both the previous position of the rocks and their later disturbance is uncertain. The present attitude of the pre-Cambrian surface as determined by Moss (1936, Pl. 2) is suggestive as to the initial dips. While the amount of dip of this surface has been more recently altered, probably the directions have not been substantially changed since the late Paleozoic. In Pennsylvania the directions are the same as shown by Price (1931, p. 40) for the base of the Silurian at the close of Pottsville time. If this agreement holds for the area studied, the initial dips of the mid-Paleozoic strata must have been in directions essentially the same as at the present time. The dip of the surface formations and of the pre-Cambrian surface agree in the eastern half of New York, though to the southwest this is not true; the axis of the trough as defined by surface rocks lies 20-40 miles northwest of the axis along the pre-Cambrian surface. The regional dip existing immediately after the jointing occurred is unknown because the magnitude and character of more recent warping is still uncertain. Consequently, any possible effect of regional warping in causing the joints cannot be evaluated, though it probably was considerable.

AGE OF JOINTS

GENERAL CONSIDERATION

The relationships of the joint sets to other structures indicates their age, a matter of genetic importance. Observations indicate that when the stresses of the Appalachian Revolution began to deform the rocks of this area, jointing was the first effect. The evidence leading to this conclusion pertains to the folding, faulting, warping, and dike intrusion.

FOLDING

The joints apparently antedate the folds because the folding has disturbed their typical vertical position. Later folding should cause strike

joints to hade so as to converge below the anticlines and to have little or no effect on dip joints. The usual hade of joints in horizontal strata, however, ranges from 0° to about 5°, an amount exceeding the usual dip of the strata. In general, then, tilting of the joints as a result of later folding is difficult to detect.

Nevertheless, in places the strata dip steeply, and the joints have been rotated from their normal positions. They lie essentially perpendicular to the bedding planes, tilted into various positions depending on their relations to the strike of the strata and on the amount of the dip. At two outcrops in the Coxsackie quadrangle where the strata dip steeply, the joints appear to be arranged haphazardly. However, when the positions were determined which these joints would occupy if the strata were restored to the horizontal, in each case they corresponded to the normal joint pattern for the quadrangle. In the Towanda quadrangle on the south flank of the Rome anticline, dips of 16° to 38° occur. The joints of Set I here strike nearly at right angles to the strike of the strata and their hade is only a few degrees to east or west. The Set II joints, however, have about the same strike as the strata, and hade to the north the same amount that the beds dip south. The joints of Set II, then, must have been formed before the folding. The presence near Ithaca of peridotite dikes in the joints of Set I only, indicates that this set was formed either before or simultaneously with Sets II and III, so Set I must also have preceded the folding. Definite effect of the folding on Set III was not found. Sheldon (1912) observed that the hade of these joints was in the same direction as the dip of the strata, and further, that folds not strong enough to reverse the dip (that is, terraces) did reverse the joint hades. Whether this minor dependence on the folds indicates that the Set III joints are older or younger is uncertain, and the limited extent of the effect suggests a coincidence.

FAULTING

Horizontal bedding faults in the Ithaca region offset both strike and dip joints; fractures in the same rock type and with identical spacing above and below the fault are displaced a few inches to several feet. In various parts of the area thrust faults disturb the normal joint positions, so that the jointing must have occurred before the faulting. However, some of the faulting may be more recent than late Paleozoic.

Melton (1929, p. 746) also concluded, in regard to the Oklahoma joints, that they formed with the initial compressive stresses of the Ouachita orogeny, before folding and faulting.

WARPING

Since the present regional dip is a composite result of several earth movements, it is impossible to state confidently the age relations of warping to jointing. Warping of the geosynclinal stage certainly preceded jointing, and the fairly recent uplifts evidenced in the topography followed. Very likely tectonic torsional movements were active during most stages of the Appalachian Revolution, early as well as late, and consequently must have accompanied and affected joint formation. In precisely what way and to what extent, however, remains uncertain.

DIKE INTRUSION

The existence near Ithaca of peridotite dikes in the north-south joints has a bearing on the relative ages of the joint sets. Some 50 have been described (Filmer, 1939; 1940a; 1940b; Martens, 1924; Matson, 1905; Williams, *et al.*, 1909), ranging in width from less than an inch to about 190 feet. The dikes occur in both components of Set I and may branch where two such joints intersect. Thin tongues extend into the bedding planes (Matson, 1905, p. 268), but no dikes are known in any but dip joints. Previous authors have suggested that the confinement of the dikes to the master joints may indicate that Set I is older than the others, though it has been recognized that stress conditions at the time of the intrusion may have held the other joints closed.

That all the sets were in existence during the intrusion seems clear at several localities. The widest known dike (Filmer, 1939, p. 210), exposed in a ravine between Indian and Glenwood creeks, 3½ miles northwest of Ithaca, has zigzag boundaries usually following the Set I joints but at several places changing to Set II for a foot or more. At the foot of Taughannock Falls, 2 miles north of the Ithaca quadrangle, joints of Set III stop abruptly against thin (1–2 inches) dikes and continue precisely in line beyond the dike, which quite evidently cuts across earlier joints. Though the dikes have many transverse joints and veins (Sheldon, 1927), no instances were found where joints of Set II or III cut through sediments and igneous rocks alike. Therefore all three joint sets are believed to antedate the intrusion, though they may not be of identical age.

No effect of the folding on the dikes is known. At two localities the dikes are displaced by faults of uncertain age. Since the geologic date of the intrusion remains unknown, the dikes indicate nothing of the absolute age of the jointing but merely that all sets preceded the intrusion.

The joints themselves give no certain indications of the relative ages of the sets. At places some joints of Set III are discontinuous against Set I, but the occurrence is not definite or consistent enough to be more than suggestive; the situation may have resulted from minor strike-slip

FIGURE 1. CONJUGATE SHEAR JOINTS (SET I)
Upper Taughannock Creek, near Ithaca, N.Y.

FIGURE 2. SIMILAR SHEAR (FACING RIGHT) AND TENSION JOINTS IN SHALE (SETS I AND III)
Cayuga Lake cliffs at Ithaca, N. Y.

FIGURE 3. CONTRASTING SHEAR (FACING RIGHT) AND TENSION JOINTS IN SANDSTONE (SETS I AND II)
Unadilla, N. Y.

faulting. All sets were probably essentially contemporaneous. As was pointed out by Becker (1905), an area already jointed varies in resistance so greatly in different directions that a later stress would more probably be relieved by movement along the first joints and by granulation of the earlier joint blocks, than by the formation of a new set of joints systematically arranged. Since Sets I and II have the same relationships to each other over the entire area and pass through comparable regional variations,—in sharp contrast to the independence of Set III—they are believed to have formed in the same orogenic episode though perhaps not strictly simultaneously. Set III may have formed at the same time or later.

CHARACTERISTICS OF THE FRACTURES

GENERAL CONSIDERATIONS

The fractures of the three sets having regional development show distinctive characteristics by which the joints can usually be identified in the field independently of their positions (Pl. 1, fig. 3). This is not always possible, however. Thus the two joint sets so well exposed in the cliffs along the east side of Cayuga Lake near its southern end (Pl. 1, fig. 2) have frequently been interpreted as forming a system of conjugate shears. Their differences become apparent when the joints are traced into near-by outcrops differing in lithology. Sheldon (1912) noted differences between the strike and dip joints, but they were not emphasized and have often been overlooked by later writers.

SET I

The joints of this compound set are remarkably plane. They slice cleanly through hard concretions embedded in weak shales, and pass without deviation through extreme cross-bedding and zones of contemporaneous deformation where the strata have been complexly twisted and broken before induration (Pl. 2, fig. 2). They are characteristically vertical, though hades of 20° are encountered rarely and hades of 5° are not uncommon. The Set I joints are well developed in sandstone, shale, and limestone, especially where one rock type composes a considerable thickness of the section. Where thin beds of sandstone and shale alternate, they are developed best in the sandstone and may even be confined to that rock (Pl. 2, fig. 1). In the latter case the fractures in one layer are generally not vertically above or below those in another sandstone lower or higher. Occasionally the joint may be vertical in the sandstones and hade considerably in the intervening shales. The extent of these joints varies from a few inches to 200 feet or more both horizontally and vertically. The individual joints at each locality vary

little in strike from the mean for the set. At almost every outcrop they are the most numerous, often lying little more than an inch apart. In one instance 139 joints with almost identical strikes were counted in an area 36 feet wide. Such close spacing might suggest fracture cleavage, but the breaks are of a different character; these zones contain many joints only a few inches long but include others of identical character which extend many feet. In only five quadrangles did the joints of this set constitute less than half of all those measured, and in five quadrangles they exceeded 70 per cent.

On most of the more planar joint surfaces featherlike or flamelike markings (Pl. 3, figs. 1, 2) are found. These plumes consist of a series of minute, irregular ridges, a quarter of an inch or less wide and with a relief of about one sixteenth of an inch. The ridges are discontinuous and usually curved, arranged parallel and en echelon in groups having a straight or sinuous, indefinite axis. These axes run along the joints parallel to the bedding in either direction, sometimes for 25 feet in the thicker sandstones. Axes pointing in opposite directions on one joint surface often turn directly up or down and unite at the boundary of a layer. Usually a separate plume occurs on each layer a joint cuts, especially where sandstone and shale alternate. However, some single plumes extend over several layers, particularly in thick shales. They show most clearly in sandstone, less well in shale, and imperfectly in massive limestone. The pattern on opposite walls of a joint correspond, since the plume is the fracture surface itself, not a coating applied to a smooth break. The plumes occur on both components of Set I; in fact, in the Binghamton quadrangle a continuous pattern was observed on a single joint which followed the direction of first one component and then bent to that of the other. Similar "feather-fractures" have been described in detail by Woodworth (1896) in argillaceous rocks from eastern Massachusetts. Why the rocks broke with these peculiar surfaces is not known, though an understanding of this feature would doubtless shed much light on the mechanics of jointing.

Because the joints of Set I are clean-cut, vertical planes even in nonhomogeneous rocks, they are interpreted as resulting from shearing.

SET II

The surfaces of the joints of Set II are typically curved and irregular, with a rough, torn appearance (Pl. 1, fig. 3; Pl. 2, fig. 3) especially where the joints cut alternating rock types or strong sandstone or limestone layers. They may be fairly planar in thick shales, and are sometimes confined to that rock where shales and sandstones alternate. They are generally extensive, and though they curve both horizontally and

FIGURE 1. SHEAR JOINTS (SET I)
Restricted to sandstone. Owego, N. Y.

FIGURE 2. SHEAR JOINTS (SET I)
Cutting distorted sandstone and shale. Northeastern Owego quadrangle.

FIGURE 3. TENSION JOINTS (SET II)
In shale and sandstone. Owego, N. Y.

JOINTS IN NONHOMOGENEOUS ROCK

FIGURE 1. FINE PLUMOSE MARKINGS ON JOINT SURFACES
Wall, Owego, N. Y.

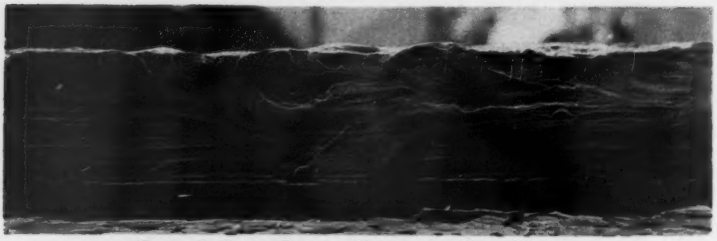


FIGURE 2. COARSE PLUMOSE MARKINGS ON JOINT SURFACE
Upper Taughannock Creek, near Ithaca, N. Y.

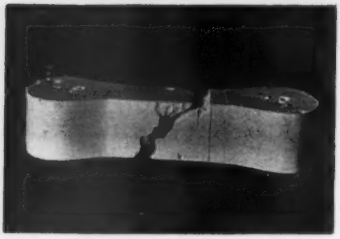


FIGURE 3. PLASTER SPECIMEN SHEARED UNDER COMPRESSION

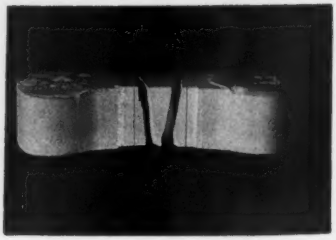


FIGURE 4. PLASTER SPECIMEN
Sheared under combined compression and tension at right angles.

JOINT SURFACES AND TEST SPECIMENS

vertically, the strike is apt to vary less than the hade. Hades as high as 25° are common, and for a single joint may vary through the vertical from one direction to the other. The strikes are more variable locally than in Set I. These joints curve gradually from one trend to another, unlike those of Set I which often bend abruptly from the strike of one component to that of the other. In most quadrangles they constitute about a quarter of the joints measured. Plumose markings are exceedingly rare on these joints.

Because the joints of Set II are typically curved and rough, especially in nonhomogeneous rocks, they are interpreted as resulting from tension. The joint system comprising Sets I and II, then, is composed of two groups of planar shear fractures intersecting at about 20°, accompanied by irregular tension breaks perpendicular to their median direction.

SET III

Set III occupies an intermediate position between Sets I and II in regard to fracture characteristics. They are usually long, vertical planes but many are curved. Although generally well developed only in homogeneous shale, as in the Ithaca region (Pl. 1, fig. 2), they are planar and numerous even in thick-bedded sandstone at a few stations in the Richmondville and Durham quadrangles. Set III joints which are vertical and planar in shale may become irregular when they pass into sandstone layers 6 or more inches thick, or may stop against such strata. While these joints dominate in some quadrangles (as, Richmondville), in general they constitute less than 15 per cent of the total. Plume marks are comparatively uncommon, usually occurring where the joint cuts thick shale but occasionally in thick sandstone beds. Plumes were found only on planar joints.

Because the joints of Set III are vertical planes mainly in weak and homogeneous rocks, and are considerably affected in character by rock variations, they are tentatively interpreted as resulting from tension also.

The contrasting characters of shear and tension joints are summarized below:

Shear Joints Set I (double)	Tension Joints Set II, and perhaps Set III
(1) Plane surfaces in all kinds of rock; cut straight through contrasting rock types, crossbedding, deformed zones, conglomerate pebbles and concretions.	(1) Plane only in homogeneous rocks; surfaces curving and rough where rock is variable.
(2) Vertical	(2) Hade variable, commonly large
(3) Numerous in strong and weak rocks alike.	(3) Commonly lacking in thick bedded rocks
(4) Strike consistent at each locality	(4) Strike more variable locally
(5) Plumose markings very common, especially in sandstone layers	(5) Plumes absent except very rarely on planar joints in thick shale

CAUSE OF JOINTING

CHARACTER OF APPALACHIAN STRESSES

Though largely independent of other tectonic structures in the area, the joints must nevertheless have been formed by the initial stresses of the Appalachian Revolution which afterwards caused the folds and thrust faults. The location of the joints, their age, and their pattern, all indicate a close relationship to the forces producing the great double-curve salient of the Appalachians in Pennsylvania and southeastern New York.

The compression causing the folds is considered to have been nonrotational in the horizontal plane. Hubbert (1928, p. 83-84) has shown that nonrotational compression causes folds which are parallel to the trend of the deformed belt, as in the Appalachian system, while rotational stress produces en echelon folds lying at about 45°. Chamberlin (1928, p. 85-90) also favors nonrotational stress because of the great length of individual folds, and because the folds and faults have parallel strikes.

Tension at right angles to the compression must have accompanied the principal stress. The arcuate pattern of the folds indicates stretching of the belt parallel to their trend. Cloos (1940, p. 855) has shown that the maximum crustal shortening occurs in the center of the bulge, and that the present doubly curving arcs are not inherited from a preceding arcuate geosyncline. This displacement of the rocks northwestward necessarily extended the area in the perpendicular direction, causing tension at right angles to the compression. The earliest bending of the strata to form anticlines and synclines under the compression would develop tension in each bed, which would be directed in the same azimuth as the compression but mainly at different angles to the horizon and at different levels from those transmitting the compression. The pitch at the ends of the folds, the undulations of their crests, and the warping uplift of the whole area would produce increments of less definitely oriented stress.

SHEAR JOINTS OF SET I

Theoretical analysis.—Because of the character of the breaks and the consistently systematic pattern of the joints of Set I, they are interpreted as resulting from shear. Under simple compression materials which do not crumble or flow fail in shear. The stress produces potential lines of shear in all directions from its point of application. Where the resistance in the perpendicular plane is equal in all directions a cone-shaped fracture occurs when the stress exceeds the strength of the material. Generally, however, any two directions in the perpendicular plane are not alike, so that the break is an oblique plane. Visualized in terms of the triaxial strain ellipsoid, conjugate fractures occur parallel to the intermediate axis and between the major and minor axes.

In the case of horizontal compression of the earth's crust, the easiest relief and greatest elongation (major axis) would presumably be upward, with the intermediate axis horizontal and at right angles to the compression. This, however, would result in fractures striking normal to the compression and dipping toward and away from it. In order to form vertical joint fractures, it is essential that lateral relief be easier than vertical. As Barrell (1926, p. 38) has pointed out, this is possible only if a tensile force acts in the horizontal direction at right angles to the compression. This stress combination also seems to be evidenced by the other later structures present.

The actual angular position of the oblique planes of shear with respect to the compressive stress depends on five variables (Lovering, 1928, p. 712): (1) strain or elastic deformation before rupturing, (2) molecular binding force or strength, (3) friction, (4) the shearing or parallel component of the stress, and (5) the normal or perpendicular component of the stress. In the zone of fracture the rocks involved must have behaved as brittle materials, so that the effect of strain was negligible. The similar character and position of joints in the different rock types indicates that the molecular binding force or strength varies little, and that this factor exercises little control on the shearing position. The friction depends on the material and also varies directly with the normal component. The coefficient of friction must vary but little in different parts of the area. Interbedded sandstones and shales prevail, which aggregate must give average values nearly equal from place to place. Consequently, the variations in the normal and tangential components control the shearing position.

The relative magnitudes of these two components on the various potential planes of shearing are given by the following formulae from Lovering (1928, p. 712) and Sheldon (1930, p. 629):

$$T = P \sin \theta \cos \theta$$
$$N = P \sin^2 \theta$$

where P is the compressive stress, T and N the tangential and normal components respectively, and θ the angle between the shear plane and the direction of the compression (Fig. 3, A). The relative values on the various potential planes of shear are shown graphically in Figure 4, where the ordinate gives fractions of the external stress and the abscissa gives the angle θ.

The tangential or shearing component causing the break is at a maximum for shear planes inclined at 45° to the compressive stress, declining to zero at smaller and larger angles. The normal component increases from zero for the plane parallel to the compression, to equality with

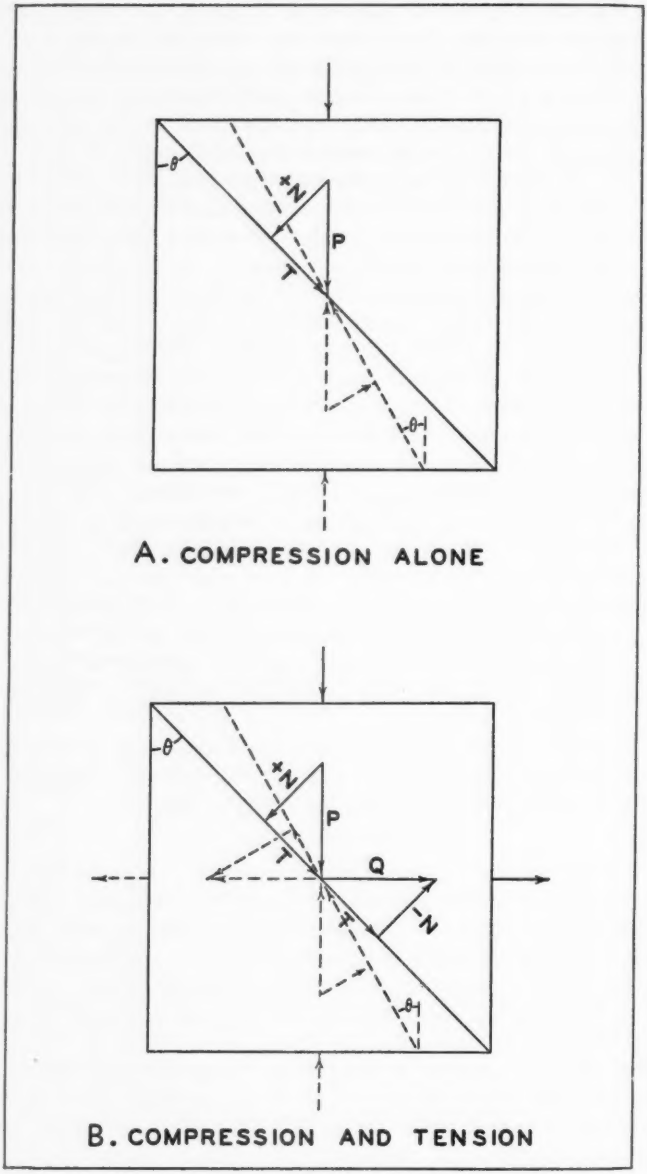


FIGURE 3.—*Resolution of stresses*
Normal and tangential components on two potential shear planes.

the tangential component at 45°, and to a maximum (same as external compression) on the perpendicular plane. This component exerts pressure on the shear plane, increasing friction and the strength of the material.

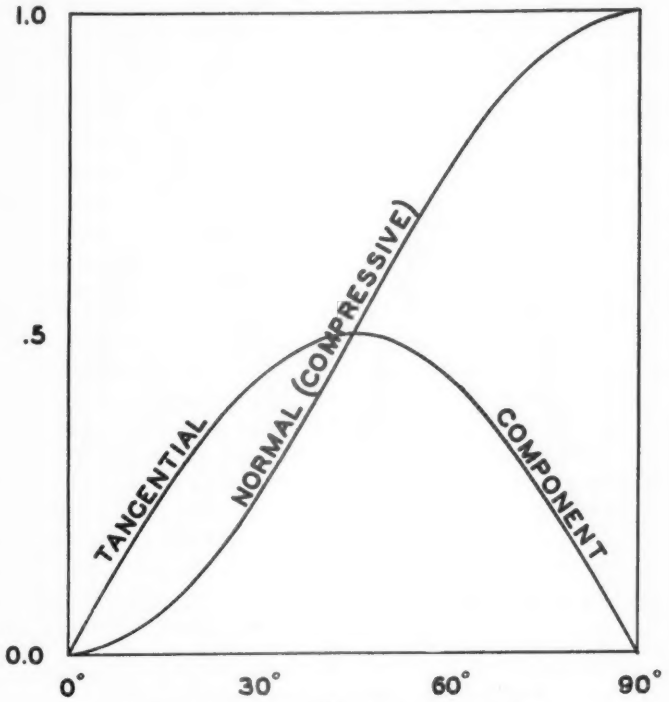


FIGURE 4.—*Relative values of stress components*
At varying angles of shear. Compression alone.

Breaks produced experimentally in brittle materials under simple compression occur not at 45° (maximum T) but at somewhat smaller angles, where the rapid decrease in the normal compression reduces friction and strength and makes shearing easier. The resulting conjugate shears lie nearly at right angles to each other, their acute intersection being bisected by the direction of compression.

The small (19°) angle between the conjugate shears of the Set I joints indicates some modifying factor. Simultaneous tension at right angles

to the compression is necessary for vertical fractures. This active tension also changes the angle of shear greatly. In such a system (Fig. 3, B) the tangential components of both the tension and the compression are

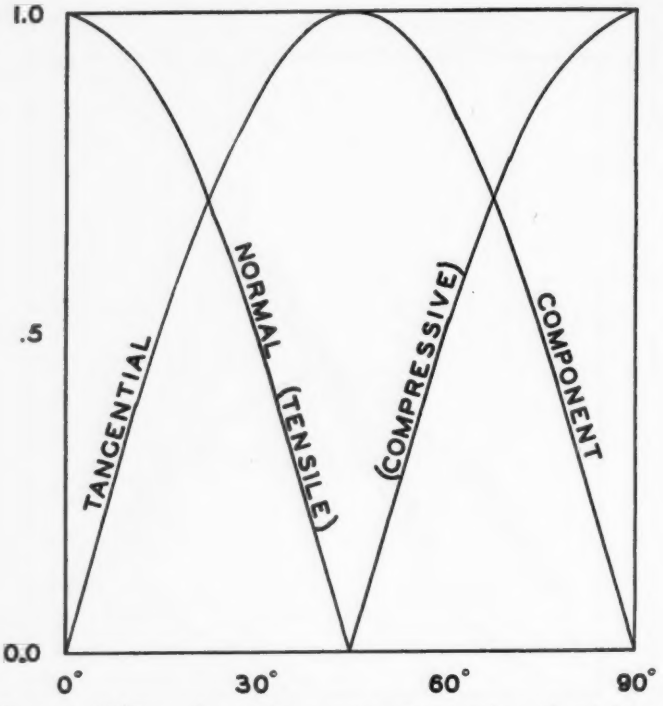


FIGURE 5.—*Relative values of stress components at varying angles of shear*
Equal tension and compression at right angles.

in the same direction and reinforce one another, while the normal components are opposed and tend to cancel each other. The total tangential and normal components for the system are given by the formulae:

$$T = P \sin\theta \cos\theta + Q \sin\theta \cos\theta$$
$$\text{or } (P + Q) \sin\theta \cos\theta$$
$$N = P \sin^2\theta - Q \cos^2\theta$$

in which P is compression, Q tension, and θ the angle between the shear plane and the direction of compression. The relative values of the combined components for the case of equal compression and tension are shown in Figure 5, the ordinate indicating fractions of either of the

stresses taken as unity, and the abscissa the angles between possible shear planes and the direction of compression.

The variations of the total tangential component are the same as in the previous case, the maximum occurring on the shear planes at 45°. In contrast, however, the normal component is zero on these planes, the algebraic sum of equal but oppositely directed resultants from the external compression and tension. The character of this normal component differs on opposite sides of this mid-point; it is compressional for greater angles and tensional for smaller angles. It reaches a maximum value, equal to one unit external stress, on planes at 0° and 90°.

Shearing at angles near 45° will be much easier in this situation than with compression alone, because no compressive normal component is present to increase friction and strength. Shearing at even smaller angles is to be expected, however, because of the weakening effect of the tensile normal component. For example, on the 22½-degree shear plane the tangential and normal components are equal and both large (each 0.7 a unit external stress). Conjugate shears intersecting at quite acute angles, bisected by the direction of compression, should occur.

Figure 6 shows the components for a combination of compression four times as great as the tension. The strong area where the normal component is compressional is here much enlarged. At the 45-degree angle, where the shearing component is still at a maximum, a considerable compressive normal component is in effect. At still larger angles it so exceeds the shear as probably to prohibit fracturing. The weak area where the normal component is tensional extends from 0° to about 27°; the two components are equal at 10°. Though the total stress here is smaller than at larger angles of shear, the resistance is low and fractures intersecting at very acute angles may be expected.

Experimental work.—Experimental confirmation of the theory that combined compression and tension at right angles would considerably lower the angle of shearing was attempted with moderate success. One method employed involved the distortion of an elastic sheet covered with a brittle coating. Different frames for stretching various kinds of rubber sheets were employed and several sorts of coatings tried. Though difficulties in controlling the applied stresses and in getting them transmitted evenly into the coating prevented a conclusive test of the theory, this method probably offers future possibilities.

More success was obtained by breaking specimens in a standard compression testing machine, to which was added a device for applying tension. This work was done in the Engineering Experiment Station laboratories at North Carolina State College. The shape of the test

specimens was modified from that employed in standard tension tests on concrete by elongating it to give a straight-sided center part 1 inch long with a 1 inch square vertical transverse section. In some cases the thickness of the specimen was made less than the height by filing

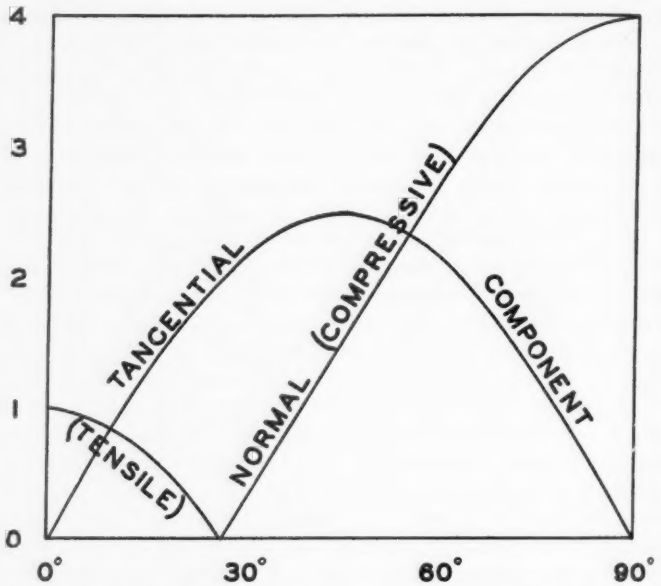


FIGURE 6.—*Relative values of stress components at varying angles of shear*
Compression four times tension, at right angles.

away the sides. Most specimens were Plaster of Paris, though a few were cement. Brittleness of the plaster specimens was insured by drying before testing. Top and bottom bearing surfaces were smoothed and trued by filing. Because the compression machine indented these surfaces, shallow notches were filed along the margins of the contact areas. In some instances grease was applied to these surfaces, but without noticeable effect.

Compression was applied by a hand crank which moved the upper head of the machine downward, the force being measured by an arm balance scale. Best results were obtained when the specimens were mounted between steel bearing plates with a steel ball between the upper plate and the descending head; this gave a more even distribution of the pressure and made it easier to adjust the specimens. The bulging

ends of the specimens were held by C-shaped grips from a standard tension-testing machine through which tension was applied from a cable system loaded with steel weights.

Specimens were broken in tension alone and in compression alone, in order to observe the contrast in failure and to determine the strengths under these simpler stresses. When tested under tension and compression together, tension not sufficient to cause failure was first applied, to insure the whole specimen's being affected. If the compression were applied first, the tension merely pulled the ends of the specimen away from the firmly held central portion. With tension applied, the position of the specimen was carefully adjusted and then compression added until failure occurred. The more rapidly the compression was applied, the more clean-cut and definite the fractures were. Lateral expansion and crumbling resulted from slow application, with irregular shear planes. Of more than a hundred tests made, about half are considered significant. In many cases the failure did not occur in the central area between the bearing plates, usually because of defective specimens or poor adjustment.

Thoroughly dried plaster specimens had a tensile strength of from 250 to 300 pounds per square inch. The breaks were relatively smooth but curved, and occurred perpendicular to the stress. The compressive strength varied considerably with age, being about 400 lbs. per sq. in. at 2 days and well over 1000 lbs. per sq. in. at 3 weeks or more. Typical diagonal shear fractures near the 45-degree position were obtained (Pl. 3, fig. 3), especially with a rapid application of the pressure.

In the tests with the combined stresses, a tension of 100 or 150 lbs. was first applied and then 250 to 400 lbs. compression added before failure occurred. In the machine used only a rough estimate of the compression could be made when it was suddenly applied. The fractures formed under these circumstances contrasted notably with the others. They tended to dip steeply with respect to the direction of compression, generally at angles of 70° to 80°, as illustrated in Figure 4 of Plate 3. Though much stronger, the cement specimens gave similar results. These tests, though not sufficiently numerous or well controlled to be absolutely conclusive, are still a significant practical confirmation of the theory.

Since the Set I joints are conjugate shears intersecting at very acute angles, they must have resulted from a combination of compression and tension at right angles. The median directions of the set, radiating out from the center of the curved salient of Appalachian folds in Pennsylvania and lying perpendicular to the folds, indicate the directions of initial regional compression. This fundamental stress, modified by the

tension at right angles arising from the northwestward bulging of the area, is believed to have formed the master joints.

TENSION JOINTS OF SET II

The consistent regional relationship of Set II with Set I indicates that both must have been formed in the same tectonic episode. The greater variability in strike and hade of Set II joints points to local rather than regional control, and their irregular, curving surfaces to a tensile origin. Since Set II generally lies nearly perpendicular to Set I, this tension must have been acting in the same general direction as the regional compression. To be effective in forming joints, tension in this position must have acted at a different time than while Set I joints were being formed. Tension in this azimuth originated with the bending of the strata even before definite anticlines and synclines formed. While bending, the strata would not be transmitting the regional compression, so that the necessary lateral relief would be present. It is suggested, then, that the initial compressive shock affected all levels of the crust and formed the Set I joints throughout the area, and that later as the strata bent (the compression being then transmitted mainly through the basement rocks), Set II fractures developed progressively in areas of local weakness. The considerable departures of the Set II joints at places from their regional position (normal to Set I) shows the powerful influence of local bending stresses associated with plunging folds, anticlinal saddles, and warping of the regional dip.

DOUBTFUL JOINTS OF SET III

The origin of Set III remains quite uncertain. They are not one component of conjugate shears as has been sometimes assumed. Their different character and constant strike over the whole region point definitely to an independent origin, perhaps simultaneous or perhaps much later. Generally they show tension characteristics, but in places they resemble shears. Their intense development in some localities and their virtual absence in adjacent ones adds to the uncertainty of their origin. Possibly they formed early during the Acadian disturbance or perhaps much later during the post-Triassic Palisade movements.

SUMMARY

The joints studied fall into sets of essentially parallel fractures. The position of each set is quite constant in small areas. When traced over large areas the positions of two of the sets change gradually and consistently, while that of the third remains constant. The most numerous set (I) is double, including two minor sets which intersect at acute angles

which average 19°. These shear fractures are plane and vertical even in strong and inhomogeneous rocks. The set has a radiating pattern for the whole area. Set II is single and consists of curved and irregular tension breaks lying roughly perpendicular to Set I, thus having a pattern of concentric arcs. Sets I and II constitute a system, formed at nearly the same time and before the folding. The third set (III) dominates locally but in general is minor. It is a single set maintaining a constant strike. All the sets show marked independence of folds, faults, and regional dip, the "dip" set in one area becoming the "strike" set elsewhere. Theory and experiment indicate that the acutely intersecting shears of Set I may result from simultaneous compression and tension acting at right angles. Set II was formed by tension alone perpendicular to the breaks. These stresses were evidently connected with the subsequent formation of the arcuate fold salient in central Pennsylvania. The origin of Set III is doubtful; it may have resulted from shearing but more probably from tension under uncertain conditions and probably at a different time.

REFERENCES CITED

Barrell, J. (1926) *Geological relations of earth condensation and resulting acceleration in rotation,* Am. Jour. Sci., vol. 11, p. 38.

Becker, G. F. (1895) *Torsional theory of joints,* Am. Inst. Min. Metall. Eng., Tr., vol. 24, p. 130-138.

—— (1905) *Simultaneous joints,* Wash. Acad. of Sci., Pr., vol. 7, p. 267-275.

Bradley, W. H., and Pepper, J. F. (1938) *Structure and gas possibilities of the Oriskany sandstone in Steuben, Yates, and parts of the adjacent counties,* U. S. Geol. Survey, Bull. 899-A, p. 30.

Bucher, W. H. (1920-1921) *The mechanical interpretation of joints,* Jour. Geol., vol. 28, p. 707-730; vol. 29, p. 1-28.

Cathcart, S. H. (1934) *Geologic structure in the plateaus region of north Pennsylvania and its relation to the occurrence of gas in the Oriskany sand,* Penn. Topogr. Geol. Survey, Bull. 108, p. 1-24.

Chamberlin, R. T. (1928) *The strain ellipsoid and Appalachian structures,* Jour. Geol., vol. 36, p. 85-90.

Cloos, E. (1940) *Crustal shortening and axial divergence in the Appalachians of southeastern Pennsylvania and Maryland,* Geol. Soc. Am., Bull., 51, p. 845-872.

Filmer, E. A. (1939) *New peridotite dikes of Ithaca,* Pan-Am. Geol., vol. 72, p. 207-214.

—— (1940a) *Peridotite dikes of Ithaca, II,* Pan-Am. Geol., vol. 73, p. 111-116.

—— (1940b) *Barriers to migration of gas,* Pan-Am. Geol., vol. 73, p. 332-336.

Hall, James (1843) *Geology of New York. Part IV. Survey of the fourth geological district,* 683 pages, Albany, N. Y.

Hubbert, M. K. (1928) *Directions of stresses producing given geologic strains,* Jour. Geol., vol. 36, p. 83-84.

Lovering, T. S. (1928) *The fracturing of incompetent beds,* Jour. Geol., vol. 36, p. 709-717.

Martens, J. H. C. (1924) *Igneous rocks of Ithaca, New York, and vicinity,* Geol. Soc. Am., Bull., 35, p. 305-320.

Matson, G. C. (1905) *Peridotite dikes near Ithaca, New York,* Jour. Geol., vol. 13, p. 264-275.

Melton, F. A. (1929) *A reconnaissance of the joint systems in the Ouachita Mountains and central plains of Oklahoma,* Jour. Geol., vol. 37, p. 729-746.

Moss, R. G. (1936) *Buried pre-Cambrian surface in the United States,* Geol. Soc. Am., Bull., 47, p. 935-966.

Pepper, J. F. (1934) *Taconic and Appalachian orogenies in the Hudson River region,* Science, n. s., vol. 80, p. 186.

Price, P. H. (1931) *The Appalachian structural front,* Jour. Geol., vol. 39, p. 24-44.

Robinson, J. F., *et al.* (1932) *Subsurface structural geology of the northern Pennsylvania and southern New York gas fields,* Penn. State College, Min. Ind. Exp. Sta., Bull. 11, p. 9-18.

Ruedemann, R. (1930) *Geology of the Capitol District,* N. Y. State Mus., Bull. 285, 218 pages.

Sheldon, P. G. (1912) *Some observations and experiments on joint planes,* Jour. Geol., vol. 20, p. 53-79, 164-183.

——— (1927) *On the association of faulting with dike intrusion,* Jour. Geol., vol. 35, p. 353-367.

——— (1928) *Note on the angle of fracture cleavage,* Jour. Geol., vol. 36, p. 171-175.

——— (1930) *Pyramidal jointing in shales,* Jour. Geol., vol. 38, p. 625-632.

Sherrill, R. E. (1934) *Symmetry of northern Appalachian foreland folds,* Jour. Geol., vol. 42, p. 225-247.

Swanson, C. O. (1927) *Notes on stress, strain, and joints,* Jour. Geol., vol. 35, p. 193-223.

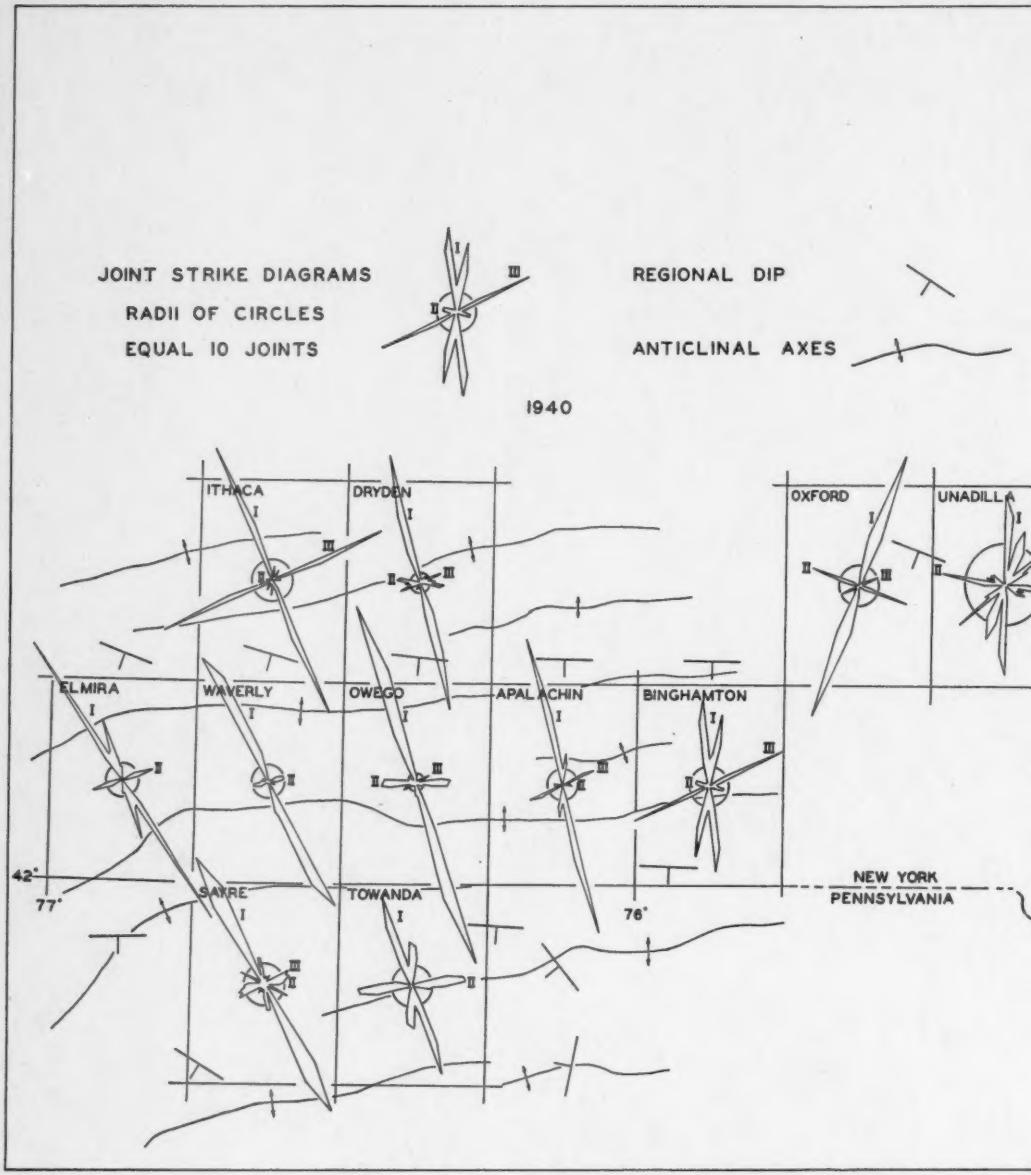
U. S. Geological Survey (1932) *Geologic map of the United States.*

Wedel, A. A. (1932) *Geologic structure of the Devonian strata of south-central New York,* N. Y. State Mus., Bull. 294, 74 pages.

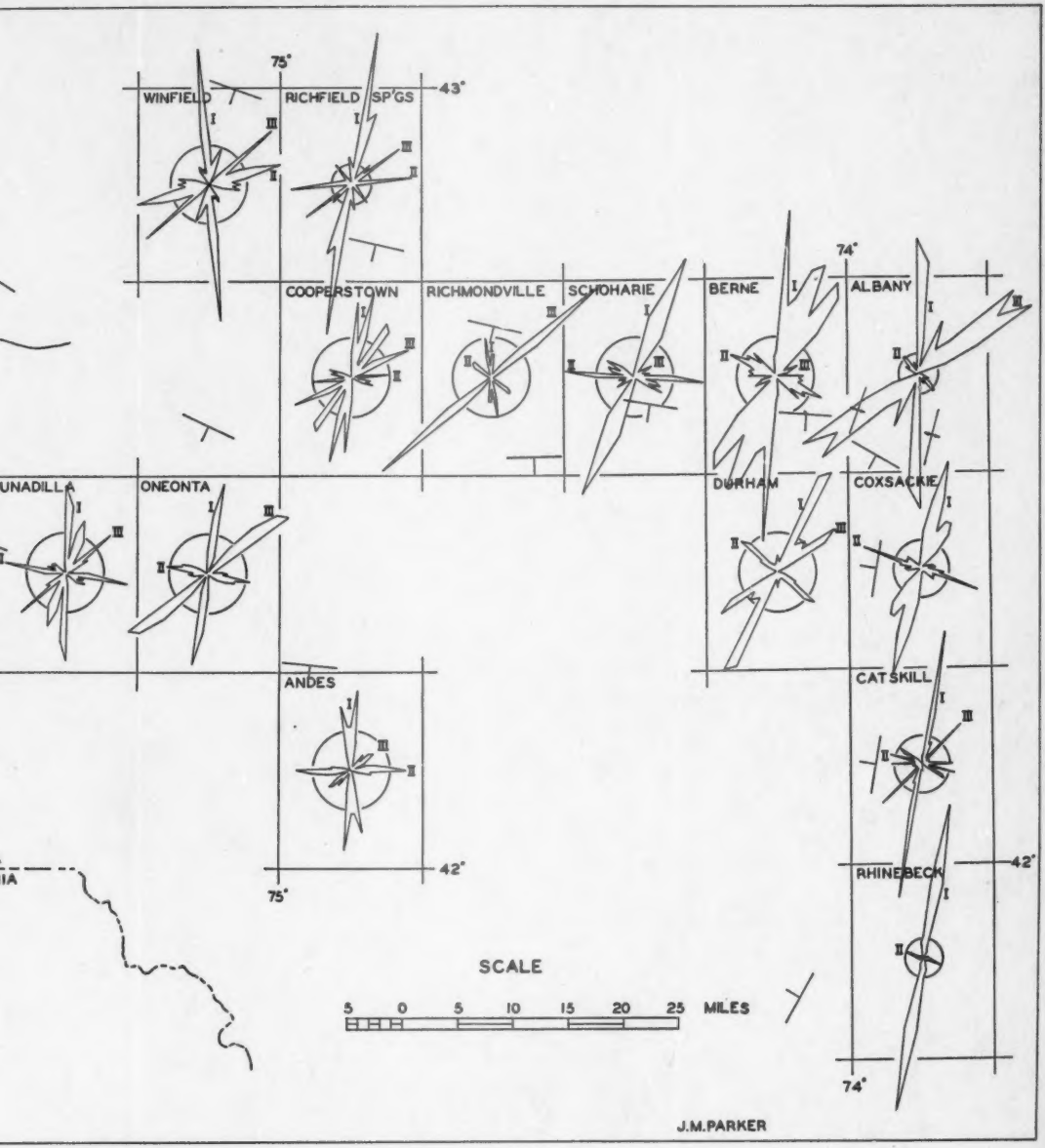
Williams, H. S., *et al.* (1909) *Watkins Glen-Catatonk, New York,* U. S. Geol. Survey, Folio 169, p. 15.

Woodworth, J. B. (1896) *Fracture system of joints,* Boston Soc. Nat. Hist., Pr., vol. 27, p. 163-183.

North Carolina State College of Agriculture and Engineering, Raleigh, N. C.
Received by the Secretary of the Society, October 29, 1940.
Read by title, December 28, 1940.



MAP OF PARTS OF NEW YORK AND PENNSYL



PENNSYLVANIA SHOWING STRIKES OF JOINT SETS

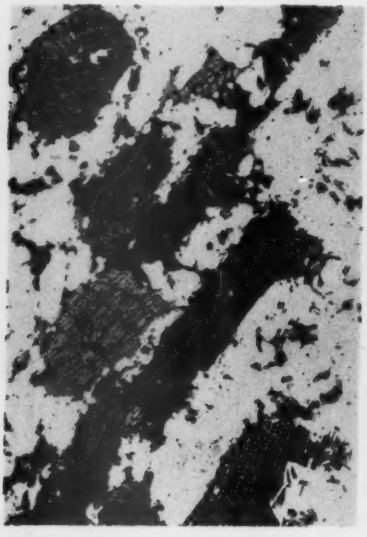


FIGURE 1. PRISMATIC HORNBLENDE IN DIORITE X 8

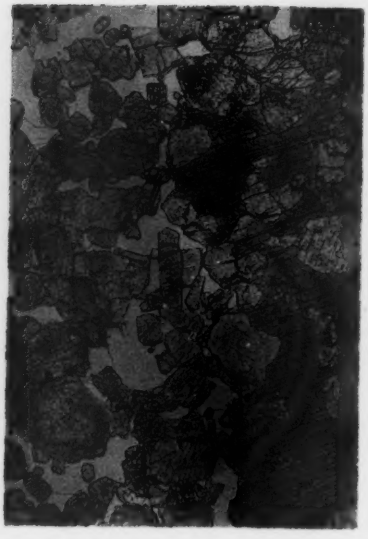


FIGURE 2. NORITE PASSING INTO HORNBLENDE PYROXENITE. X 16

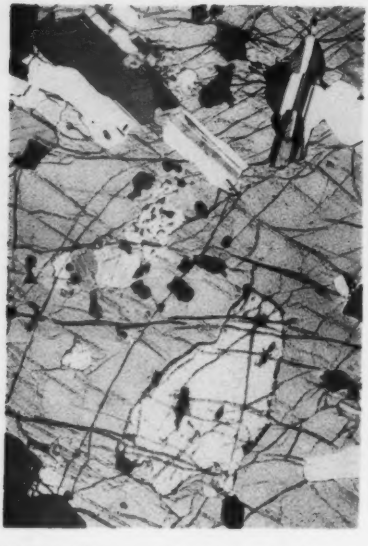


FIGURE 3. POIKILITIC HORNBLENDE IN NORITE X 16

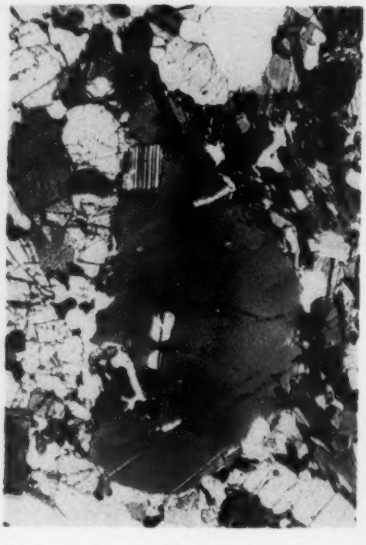


FIGURE 4. LENS OF "SHAGREEN" ORTHOCLASE IN NORITE. X 16

PHOTOMICROGRAPHS

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 53, PP. 409-428, 2 PLS., 1 FIG. MARCH 1, 1942

PHASE PETROLOGY IN THE CORTLANDT COMPLEX, NEW YORK

BY S. JAMES SHAND

CONTENTS

	Page
Abstract	409
Statement of the problem	410
Summary of Rogers' sections	412
Evaluation of Rogers' work	413
Phase petrology: critical phases	414
Discussion of individual phases	415
Hornblende	415
Spinel (pleonaste)	418
Olivine	420
Biotite	421
Quartz, orthoclase, and micropegmatite	422
Plagioclase	422
Augite and hypersthene	423
Garnet and epidote	424
History of the complex	425
Acknowledgments	427
References cited	427

ILLUSTRATIONS

Figure	Page
1. Structural map	410

Plate	Facing page
1. Microphotographs	409
2. Geological diagram of the complex	428

ABSTRACT

The Cortlandt complex, near Peekskill, New York, is formed of rocks that range from peridotite and pyroxenite through norite to diorite. G. S. Rogers mapped 14 species of these rocks and added syenite and sodalite syenite to the list. Robert Balk made a structural survey of the complex and showed it to be a funnel-shaped pluton within which three smaller funnels are developed. If these funnels mark channels through which magma ascended, the various species ought to be grouped more or less symmetrically about the funnels; yet Rogers' petrographic map shows little correspondence with Balk's structural map. The explanation lies in the indefinite character of Rogers' species, which grade into one another in every respect. Progress in understanding the complex requires the abandonment of "species petrology" in favor of "phase petrology" or the mapping of critical mineral phases. The most instructive phase is hornblende, which occurs in two forms, one

primary and the other a poikilitic replacement of plagioclase and pyroxene. The first is confined to the marginal zone; the second is found all through the central region, extending far beyond the boundary of Rogers' "hornblende-norite." Balk's central funnel falls entirely within this enlarged hornblende field. The marginal zone of the pluton is characterized by primary hornblende, by the frequent appearance of biotite in large poikilitic plates, and by the occasional development of poikilitic garnets, orthoclase, and micropegmatite. The occurrence of sodalite syenite is not confirmed.

STATEMENT OF THE PROBLEM

The petrology of the Cortlandt eruptive complex (Cortlandt series) was first studied in detail by G. H. Williams (1886), following pioneer work by J. D. Dana. Williams made no map, but he furnished care-

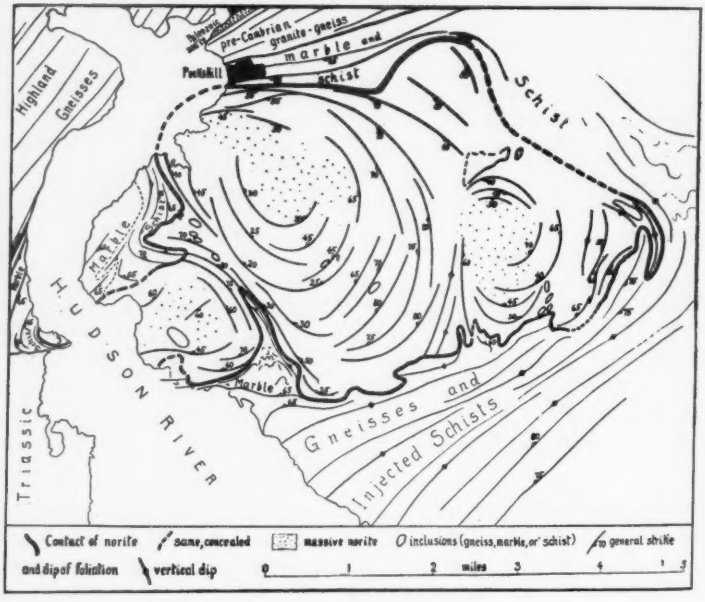


FIGURE 1.—*Structural map*

After R. Balk (1937, p. 92, Fig. 33).

ful petrographic descriptions of many varieties of diorite, norite, gabbro, pyroxenite, and peridotite that occur in the region. Twenty-five years later, G. S. Rogers made the first map of the complex and indicated on it the distribution of 17 so-called "rock-types", which include syenite and sodalite syenite in addition to the varieties previously recognized by Williams. The form and structure of the complex were not discussed

by Rogers, and it was not until 1927 that a structural survey, made by Robert Balk, showed the complex to be a funnel-shaped mass within which two or perhaps three smaller funnels are recognizable (Fig. 1).

Williams supposed the different kinds of rock to have been intruded successively, in order of increasing acidity, and Rogers expressed the same opinion. Yet Williams (1886, p. 27) stated that

> "no sharp line can be drawn between the different groups . . . on the contrary, every possible transition from each group into every other occurs. . . . I know of no other region of massive rocks so well calculated to show the transitions, both sudden and gradual, of one rock type into another."

Rogers too recorded the gradual passage of diorite into hornblendite, of diorite into norite, and of norite into olivine pyroxenite. It seems to follow from these statements that the intrusion of the complex was essentially a single act.

Now if all the main rock types belong to a single period of intrusion, and if the structural funnels mark the channels through which the magma ascended, then one would expect to find some correlation between structure and petrology. The cores of the funnels, for instance, might be of one kind of rock around which the other kinds would group themselves in a rudely concentric manner; or, if Harker's suggestion of the simultaneous intrusion of two different magmas were favored, then each core might be expected to show a different kind of rock, with zones of progressive hybridism between them. Or again, if the dioritic member was formed in consequence of assimilation of Manhattan schist by norite, as Rogers seems to have suspected; or even if all the feldspathic members of the complex had resulted from the action of "alkaline emanations" upon schist, as D. L. Reynolds lately contended, a more or less concentric arrangement of the rock types could hardly fail to appear. Yet a comparison of Rogers' petrographic map with Balk's structural map fails to show any such correlation. Balk's northwestern funnel is partly in hornblende norite, partly in biotite norite, the boundary running diametrically across the funnel. Balk's southeastern funnel is partly in peridotite and partly in pyroxenite. The small southwestern funnel encloses portions of areas mapped by Rogers as pyroxenite, norite, and diorite respectively. In the spaces between the funnels there is hardly a suggestion of any orderly arrangement of the rock types.

This apparent lack of correlation between structure and petrology presents an invitation to further study of the complex, for it is clear that if any correlation can be established it will throw light upon the history of intrusion and the genesis of the rocks. In comparing the two maps one cannot fail to observe that Balk's map contains nothing of a subjective character; a rock is either banded or it is not, and there

can be no two opinions about the matter. But Rogers' map contains much that is subjective. Since the various rocks grade into one another, it must be largely a matter of opinion where the boundary line is to be drawn between two rock types such as biotite norite and biotite-augite norite, or between the latter and hornblende norite. The position of such a boundary depends on the observer's concept of a "rock type". It is possible that another observer, holding a different concept, would have traced the boundaries differently. Before we can assess the value of Rogers' map we must have a clear picture of what he meant by each of the "rock types" he indicated on it.

The first step toward forming such a picture was to make a critical study of Rogers' thin sections, which are preserved in Columbia University. Rogers tells us that he collected 25-30 specimens to the square mile and that he examined altogether 260 thin sections. Unfortunately only 159 thin sections have survived, and the corresponding hand specimens have not been preserved. Among the labeled slides only one bears the name syenite, one sodalite syenite, and one monzonite. Diorites number 14, norites and gabbros 52, hornblendites and pyroxenites 27, olivine-pyroxenites, peridotites, and serpentines 15, besides 13 contact rocks and a further 36 slides without labels.

In naming the rocks Rogers was clearly influenced by Dana and Williams, who based their nomenclature on the predominant dark mineral; thus the name norite implies predominant hypersthene; gabbro, predominant augite; diorite, predominant hornblende or mica with little or no pyroxene. Although Rogers determined the composition of the plagioclase in most of his rocks he made no systematic use of this factor in naming his specimens; thus his diorite is the diorite of Zirkel, not that of Rosenbusch.

SUMMARY OF ROGERS' SECTIONS

SYENITE: The only slide bearing this label shows a very unfresh rock in which the feldspar is mainly plagioclase. Another slide contains both orthoclase and plagioclase, together with hornblende and biotite, and might pass for monzonite. Rogers admitted that syenite "is not well defined" and hinted at its formation by reaction between norite and schist. In this he was probably correct. Fresh specimens collected about the localities indicated on the map have not disclosed any mappable body of rock that might be called syenite.

SODALITE SYENITE: This identification cannot be sustained. The single thin section shows an unfresh dioritic rock with zeolitic alteration products. New material collected about the locality indicated by Rogers is hornblende-mica diorite.

DIORITE: This name was given by Rogers, as by Williams, to rocks containing plagioclase together with either hornblende or biotite, but with little or no pyroxene. Rogers' thin sections show the following dark minerals: hornblende alone; hornblende-biotite; hornblende-hypersthene; hornblende containing cores of augite;

biotite almost alone; biotite-hypersthene. Epidote is abundant at two localities, and poikilitic garnets are often observed near contacts with Manhattan schist. In many of these dioritic rocks the plagioclase shows strain, crushing, and even granulation.

This is a very ill-defined group. Some part of it may be magmatic diorite, but some is ortho-gneiss, and much of it is norite which has been contaminated by assimilation of schist. Rogers (1911, p. 59) remarked that "in many places where there is reason to believe that inclusions have existed but have been absorbed, diorite is found."

GABBRO: Three slides in the collection, bearing this label, are richer in augite than the average norite of the complex but are not sufficiently different to justify the change of name.

BIOTITE NORITE: Rogers tells us that this rock cannot be distinguished in hand specimen from biotite-augite norite. It follows that no reliable boundary could be traced between these rocks without the study of a large number of thin sections; yet there are only 8 sections bearing this label, or less than one section to each mile of boundary line. Some of these sections contain augite, and others have very little biotite, so it is clear that the boundary has no real significance.

BIOTITE-AUGITE NORITE: This rock differs from the last only by an increasing content of augite in addition to the ubiquitous hypersthene. Hornblende is said to be rare, and Rogers' thin sections are mostly free from it, but there are only 20 sections in all. The writer has found hornblende norite at many points within the areas marked biotite-augite norite on the map.

HORNBLENDE NORITE: In this rock hornblende and hypersthene are the characteristic dark minerals, but augite is always and biotite is frequently present in addition. In the field it is often impossible to distinguish rocks that contain hornblende from those that do not; this is a consequence of the intimate intergrowth of hornblende with augite and hypersthene. As there are only 11 thin sections of hornblende norite in the collection it is clear that Rogers' boundary lines cannot accurately represent the distribution of hornblende in the norite.

HORNBLENDE-BIOTITE NORITE: This is a variety of hornblende norite containing a little more biotite than usual. There is no sufficient reason for mapping it as a distinct type.

PYROXENITE: Rocks so named are supposed to be free from olivine, but Rogers admitted that they cannot be distinguished megascopically from those that contain small amounts of this mineral. With the entrance of hornblende this rock grades into hornblende pyroxenite and hornblendite.

OLIVINE PYROXENITE: These rocks are richer in olivine, but Rogers (p. 40) says "the areas in which olivine is segregated . . . are probably not as well defined as depicted on the map"; and he repeats on page 44 that "the areas occupied by chrysolitic rocks are rather vaguely defined." With the entrance of hornblende this rock grades into hornblende-peridotite and cortlandite.

BIOTITE PERIDOTITE is represented by a single thin section.

EVALUATION OF ROGERS' WORK

This comparison of Rogers' map with his thin sections reveals nothing at all to his discredit. It is evident that he carried out his investigation with energy and assiduity, both in the field and in the laboratory. The defects of the map result from two circumstances beyond his con-

trol. The first of these is the banded character of the Cortlandt rocks. The norite of the Cortlandt complex is not strongly differentiated, like that of the Bushveld or the Stillwater complex, into anorthositic and pyroxenitic bands which differ greatly in appearance and composition. The bands in the Cortlandt norite tend to differ in grain size more than in color, and this type of banding is not very noticeable unless one looks for it. Nevertheless there are few outcrops of norite or pyroxenite in the Cortlandt area where some degree of banding cannot be observed. Along with differences in grain size there go certain less conspicuous mineralogical differences. The most fine-grained bands generally have hypersthene as the only dark mineral. Rocks of slightly coarser grain have biotite and augite in addition; and in the coarsest bands there is generally more or less hornblende. The consequence is that a single outcrop may contain two or even three of Rogers' types.

The other circumstance which affected Rogers' work adversely is the poor quality of his thin sections. Most of them are too small to present a fair sample of the mineralogy of a coarse-grained rock, all of them are thick, and in any case there are too few of them. The mapping of 25 square miles of complexly intermingled basic rocks demands many more and much better sections than Rogers had at his disposal. It is clear that he relied too much upon "hand-specimen petrology" in a region which exposes the utter inadequacy of that method of study.

For both of these reasons the boundary lines on Rogers' map do not separate rocks that are fundamentally different from one another, but only bodies of rock that contain by rough estimation more hornblende or less hornblende, more augite or less augite, more biotite or less biotite, more olivine or less olivine. These distinctions are too vague to afford a clear picture of what happened during the emplacement and crystallization of the complex.

PHASE PETROLOGY: CRITICAL PHASES

In studying the equilibrium between two or more phases of a chemical system the proportions of the phases are not important. What is important is to know which phases were increasing and which were disappearing, at a particular time, in every part of the system. If we wish to make progress in understanding the Cortlandt complex we shall have to abandon the traditional practice of mapping "rock types", which characterize the observer rather than the rocks, and proceed instead to map the distribution of critical phases which afford clues to the cooling history of the system. In short, we must abandon "species petrology" and put "phase petrology" in its place.

What is a critical phase? As the term is used here it means any phase which is restricted either to a particular part of the eruptive complex or to a particular period in the cooling history of the magma, and which may in consequence yield information about the chemical and physical changes that accompanied the freezing of the system. Plagioclase, augite, and hypersthene give little information of this character, for they are widely distributed in the Cortlandt complex and they persisted from the beginning to the end of the period of magmatic crystallization. But hornblende is a critical phase, for it is limited both in place and in time. Olivine is also a critical phase, and so are spinel, garnet, epidote, and micropegmatite. Even biotite, in spite of its ubiquitous character, has some value in this respect. The distribution, characters, and significance of the critical phases in the Cortlandt complex will now be discussed.

DISCUSSION OF INDIVIDUAL PHASES

HORNBLENDE

Williams recognized both green and brown hornblende in the complex and claimed that

> "the two types of diorite produced by the presence of brown and of green hornblende are quite distinct both in their occurrence and relationships. The former is always associated with pyroxene rocks and tends to pass gradually into norite, gabbro, or pyroxenite. The diorites composed of green hornblende, on the other hand, show their closest relationship to the mica-bearing rocks." (1888, p. 440.)

But Williams (1888, p. 441) also recognized that the color of the hornblende is sometimes intermediate between brown and green. It would be correct to go further than this and say that the color of the hornblende is seldom either pure green or pure brown, and that to describe it one must often use expressions such as greenish-brown, olive brown, or brownish-green. In some cases the mineral is mottled, some parts being green and others brown, and then it may be noticed that the brown color is developed particularly about cracks, the green in the areas between the cracks.

Examination with the universal stage failed to show any pronounced or constant difference between the two varieties of hornblende. A number of measurements made upon different samples of the brown hornblende gave the following results: extinction ($c \wedge Z$) $= 5° - 14°$; optic axial angle $= 68° - 80°$ (negative). An olive-green hornblende gave $c \wedge Z = 15°$, $2V\ (X) = 78°$. It is evident that we have to do with a continuous series of hornblendes intermediate between common hornblende and basaltic hornblende; and we may suspect that the change

of color from green to brown is connected with the degree of oxidation or hydration of the iron present.

New evidence fails to confirm Williams' claim that the rocks containing brown and green hornblende, respectively, are distinct in their occurrence and relationships. It is true in a general way that green hornblende is found especially in rocks containing little pyroxene or much biotite, and brown hornblende in rocks containing much pyroxene and little biotite; but there are exceptions to both statements. In 29 thin sections of diorite it appears that the hornblende is green in 14 cases, brown in 5 cases, and intermediate in 10 cases. In 47 sections of hornblende norite, brown hornblende appears 37 times and green or greenish 10 times. In 21 sections of pyroxenite and peridotite the hornblende is brown in 18 cases and intermediate in 3.

The habit of the hornblende crystals is more significant than their color. There are two varieties of habit, prismatic and poikilitic (Pl. 1, figs. 1-3). In some rocks the hornblende is prismatic but tends at its margins to be molded on feldspar or pyroxene, thus showing a transition from prismatic to poikilitic habit; nevertheless the primary habit is always clearly distinguishable. The prismatic habit appears in rocks with little or no pyroxene; the poikilitic habit is characteristic of all the rocks with abundant pyroxene. It follows that a green color is usually associated with prismatic habit and a brown color with poikilitic habit; but this is not an invariable rule. The difference of habit affords a much sharper basis of distinction than the difference of color.

The prismatic (idiomorphic to hypidiomorphic) habit clearly indicates that the hornblende crystallized at a comparatively early stage in the cooling history of the rock, whereas the poikilitic habit indicates that the hornblende was formed later than either plagioclase or pyroxene. It is curious to note how reluctant the earlier observers were to place the obvious interpretation on this poikilitic habit. Williams (1884, p. 261-264) described the paramorphism of pyroxene to brown hornblende in the pyroxenite of Montrose Point, as well as the poikilitic texture of the hornblende in the peridotite of Stony Point; yet he argued that the hornblende in the latter rock was formed from a residual magma. He pictured a process by which augite, hypersthene, and olivine separated from the magma at an early stage,

> "leaving the remaining portion, which must have had almost exactly the composition of the brown hornblende, in a more or less pasty condition until the succession of a lower temperature . . . finally allowed it to solidify" (1886, p. 33).

In a footnote (1886, p. 29) he says the supposition that the brown hornblende of the Cortlandt peridotites may have originated from the paramorphism of augite is "wholly untenable."

Rogers followed Williams in distinguishing rocks with green hornblende from those with brown hornblende, but the difference in habit does not seem to have aroused his curiosity. J. L. Gillson and J. E. A. Kania (1930, p. 511) were the first to see the significance of the poikilitic hornblende; they wrote "The suggestion is advanced here that these poikilitic grains are entirely or partly deuteric, and formed at or after the close of the pyrogenetic crystallization, and partly or entirely by replacement." J. W. Butler (p. 549) remarked upon the large crystals of poikilitic hornblende in the melanic norite of Emery Hill and considered them to be an indication of "endomorphism" in the contact zone. But these three writers were concerned primarily with the emery deposits and did not apply their ideas to the complex as a whole.

New evidence shows that Williams was right in claiming that some of the brown hornblende was formed by paramorphism of augite and hypersthene but almost certainly wrong in supposing this hornblende to represent the residual magma which remained after olivine, hypersthene, and augite had crystallized out. Under the microscope one can trace every stage of the replacement, not only of the two pyroxenes but of plagioclase as well, by plates of hornblende which enclose the corroded but undissolved remnants of these three minerals. Proof that the poikilitic hornblende was formed when the rock was entirely solid is found in some of the rocks that have suffered crushing; for the feldspar shows granulation and mortar structure and has most irregular extinction, while the hornblende plates which ramify through this granulated base have often escaped crushing and show normal extinction. In other instances one may see that certain bands in the norite contain hornblende, while other bands, even in the same thin section, are free from it; or again the hornblende may have developed in spots, from which it grew out like a fungus into the normal norite. Many such observations point to the conclusion that the hornblende in all the pyroxene-rich rocks of the Cortlandt complex was formed after these rocks had completed their magmatic crystallization. It is a deuteric product, not a magmatic product.

The formation of an amphibole from a rhombic and a monoclinic pyroxene may be represented by a very simple equation, as follows:

$$\underset{\text{diopside}}{2\,Ca(Mg,Fe)Si_2O_6} + \underset{\text{hypersthene}}{4\,(Mg,Fe)SiO_3} + H_2O = \underset{\text{hornblende}}{Ca_2(Mg,Fe)_5H_2Si_8O_{24}} + (Mg,Fe)O$$

When plagioclase too enters into the reaction, the product is an aluminous amphibole in which 3 Mg″ is replaced to an unknown extent by 2 Al‴, besides a possible replacement of some Si by Al and of Ca by Na.

The equation then becomes very complicated, but for the purpose of illustration we may write it as follows:

$$\underset{\text{diopside}}{Ca(Mg,Fe)Si_2O_6} + \underset{\text{anorthite}}{CaAl_2Si_2O_8} + 4\ \underset{\text{hypersthene}}{(Mg,Fe)SiO_3} + H_2O$$
$$= \underset{\text{hornblende}}{Ca_2(Mg,Fe,Al)_5H_2Si_8O_{24}} + x\ Al_2O_3 + y\ (Mg,Fe)O$$

It is now time to examine the distribution of the two varieties of hornblende. Within the norite-diorite region of the complex, prismatic hornblende is confined to a marginal belt about ½ to ¾ mile wide in the west and southwest; poikilitic hornblende occurs only in the central part of the intrusion; and between the two regions there is an irregular belt about ½ mile wide in which the norite is typically free from hornblende. The three areas so defined are not sharply bounded, for an occasional hornblendic band may be found in the middle region, and an occasional band without hornblende even in the hornblendic core; this results from the banded structure of the complex and the tendency for hornblende to form in the coarser bands. But the general shape of the region of poikilitic hornblende is shown on the map (Pl. 2); it conforms unmistakably to the curves of the foliation as mapped by Balk and it completely encloses Balk's northwestern core or funnel. Thus the mapping of this single phase seems to confirm Balk's contention that the intrusion as a whole is funnel-shaped.

Poikilitic hornblende also makes its appearance in pyroxenite and peridotite at both ends of the complex, but its distribution is less symmetrical than in the norite. In the Emery Hill-Salt Hill tract the strongest development of poikilitic hornblende is found in the rocks that lie nearest to the norite, the junction between feldspathic and nonfeldspathic rocks being often obscured by the extensive hornblendization of both. Farther east, hornblende becomes scarce and most of the rocks are entirely free from it. This observation seems opposed to Balk's idea that the Dickerson Hill mass occupies an independent funnel, since the distribution of hornblende is not symmetrical with regard to it. At Montrose Point and Stony Point the distribution of hornblende does not conform to any simple pattern.

SPINEL (PLEONASTE)

All previous accounts of the spinel in the Cortlandt complex have discussed it as an ore mineral, and its occurrence as a rock constituent has been almost overlooked. Williams (1886, p. 37) made only a single reference to spinel as an accessory mineral in the hornblende peridotite of Stony Point. Rogers did not record the presence of spinel in any of his rock sections. Gillson and Kania, as well as Butler, were ex-

pressly concerned with the ore deposits and not with the general petrology of the complex, but Gillson and Kania (p. 516) recorded spinel grains in norite in at least one instance. Bowen (1922, p. 551) contributed a theoretical discussion of the genesis of corundum, spinel, and cordierite by reaction between the magma and the surrounding schist. None of these writers seems to have known that pleonaste is not uncommon as a minor constituent of norite and diorite throughout the complex. It was observed in about 20 per cent of the thin sections of norite and diorite that were made for this investigation. About half of the spinel-bearing specimens come from the central region of the complex, between Washington Street and Dickerson Hill, and they were collected through a vertical range of several hundred feet. The sections of nonfeldspathic rocks (pyroxenite, hornblendite, and peridotite) did not reveal a single grain of spinel, except in one specimen of cortlandite from Stony Point.

The mode of occurrence of the spinel in these rocks is peculiar. With only one observed exception (the cortlandite just mentioned) the spinel is always enclosed in or intergrown with little irregular plates or skeletons of an iron ore which also encloses grains of pyrite. If this iron ore has the same composition as that in the emery deposits, it is a mixture of magnetite and ilmenite, the former predominating. (*See* analyses given by Williams, 1887, p. 197; also Rogers, p. 64.) The plates are molded on hypersthene, plagioclase, and hornblende, so there can be no doubt that they were formed at a very late stage. The rocks which carry most spinel are rich in brown hornblende and generally poor in biotite; only one section shows a little spinel in entire absence of hornblende.

Admitting the danger of drawing conclusions about the distribution of accessory minerals from the examination of thin sections only, these observations strongly suggest that the spinel in the norites and diorites is not a product of contact action. It seems more likely that it is a by-product of the reaction that gave rise to the brown hornblende, as described above. The equation given shows that when plagioclase enters into the reaction there will generally be some liberation of alumina as well as oxides of magnesium and iron. These oxides may combine immediately to form pleonaste, or under other conditions they may enter biotite, thus being retained as rock constituents. But one cannot fail to note that the same oxides, if carried outward by escaping solutions, are capable of giving rise to the aggregates of pleonaste, corundum, magnetite, garnet, högbomite, and sapphirine which constitute the massive emery ore. This possibility is not easily harmonized with Butler's contention that the emery was formed by emanations traveling in advance

of the magma into the country rock, for the spinel and magnetite of the interior of the complex were clearly formed at a very late stage in the cooling history of the magma. The new observations are in better agreement with the opinion expressed by Gillson and Kania (p. 526) that the ore deposits "were formed by gaseous or liquid emanations from the magma reservoir which passed upwards through the already solid border of the igneous mass, and into the schist".

The new observations do not exclude the possibility that the spinel of the emery deposits may have had a different origin from the spinel of the central complex, but they seem to make such an assumption unnecessary.

OLIVINE

This phase may form as much as 60 per cent of some of the hypermelanic rocks, but a more usual proportion is 10–20 per cent. Rogers made a distinction between pyroxenite, olivine pyroxenite, and peridotite according to the amount of olivine present, the limits chosen being one-fifth and one-third of the bulk of the rock. Since the presence or absence of a critical phase is more important than its precise amount, these artificial distinctions tend only to complicate the map of the complex and make its interpretation more difficult. Rogers indicated two areas of olivine pyroxenite at the east end of the complex, but admitted that they are probably not so well defined as they appear on the map. If one maps the distribution of the phase, olivine, instead of the arbitrarily defined rock type, olivine pyroxenite, there appears to be just a single region throughout which olivine is present in the majority of the rocks exposed. This region takes in the whole of Dickerson Hill and all but the eastern spur of Salt Hill, along with the valley between them. The rocks are banded, although this structure is less conspicuous in these melanic rocks than in the norite, and some bands are free from olivine; nevertheless the region as a whole is characterized by the presence of olivine, and this phase has not been found beyond the limits indicated. Rogers has mapped olivine pyroxenite among the rocks east of the Croton reservoir, but the writer found no olivine in the few rocks he collected there.

At the west end of the complex olivine appears again at Montrose Point and Green's Cove and also in the well-known occurrence of "cortlandite" at Stony Point, directly across the Hudson River from Montrose Point. These three occurrences may perhaps be enclosed within one boundary, although outcrops are too few to make this certain.

The olivine occurs mostly in irregular grains, interlocking with grains of pyroxene in an allotriomorphic aggregate. Olivine is often enclosed or partly enveloped by pyroxene, but the latter is very rarely enclosed

in olivine. It seems likely that olivine began to crystallize first but was soon joined by pyroxene. As a rule the olivine grains are smaller than the associated pyroxenes; this applies even to peridotites in which olivine amounts to as much as 60 per cent.

The olivine is a normal, magnesia-rich variety. Measured on the universal stage in sodium light, $2V=90°$. Making a small correction for the difference in refraction between the mineral and the glass hemispheres this angle becomes about 88°, optically positive. It was not possible to separate the small olivine grains from the similarly colored augite and antigorite, so the determination of the indices of refraction by the immersion method was less certain than usual. The values indicated were $\gamma=1.695$, $\alpha=1.65$. These figures agree with the axial angle and indicate a molecular proportion of 10 to 12 per cent of fayalite in the olivine.

The presence of more olivine or less olivine in a series of banded plutonic rocks recalls the occurrence of more olivine or less olivine in bedded basaltic lavas, and the explanation that applies to the latter case may apply to the former too—namely, the settling and local accumulation of olivine crystals in the magma while it was still in movement.

BIOTITE

The biotite is nearly always brown even when the associated hornblende is green. In general these two minerals are antagonistic, though not incompatible. In many of the norites and pyroxenites biotite seems to have formed, just as hornblende does, at the expense of earlier hypersthene. Sometimes biotite and hornblende are intergrown, but more commonly each mineral keeps to itself, some hypersthene grains being mantled with biotite and others with hornblende even in the same thin section. One may even see a crystal of hypersthene which is in course of transformation into hornblende at one end and biotite at the other. The larger flakes of biotite are poikilitic, enclosing corroded grains of hypersthene and sharp prisms of apatite.

In some of the norites there is a remarkable development of big biotite plates, up to 2 inches in diameter, which lie a few centimeters apart in nearly parallel position, or in two or more sets of nearly parallel positions. The plates are of paper thinness and are highly poikilitic. This unusual feature is well exposed in Furnace Dock Road, near the southern margin of the complex, and at the house "Rockledge" on Maple Avenue, near the northern margin. The chief interest of this occurrence is that it demonstrates the remarkably late crystallization of some of the biotite, which seems to have been the very last of the deuteric silicates. There is a strong suggestion that all the biotite in the norites, pyroxenites,

and peridotites of the Cortlandt complex is deuteric, though some of the biotite in the dioritic rocks may be primary to the same extent that the prismatic hornblende in these rocks is primary.

QUARTZ, ORTHOCLASE, AND MICROPEGMATITE

In the dioritic rocks of the complex it is not unusual to see a few patches of quartz occupying angular interstices between the feldspar laths. An occurrence of orthoclase in the norite at Buchanan (formerly Centerville) was described by Williams (1887, p. 139, 243), with a chemical analysis which shows it to be unusually rich in potash. Williams noted a peculiar "shagreen" effect in this mineral, and thought it was due to "a vast number of minute oval indentations which completely cover the surface". It seemed to the writer that this appearance, which was observed in several of the new slides, might be due to minute inclusions in the feldspar. Quartz was suspected, but the analysis given by Williams comes so close to pure orthoclase as to leave no room for quartz. Yet in other parts of the same slides this curious feldspar passes into a slightly coarser aggregate which is an unmistakable micropegmatite or vermicular growth of quartz and orthoclase. It does not fill interstices but seems to have made room for itself by a process of corrosion and replacement (Pl. 1, fig. 4). Plagioclase and other grains surrounding the patches have ragged edges, and some of the plagioclase has acquired a fringe of myrmekite. Larger patches of orthoclase may form a poikilitic base in which plagioclase laths are embedded; in some cases this gives rise to a rock of monzonitic character, as at the north end of Verplanck Broadway.

A process of acidification of some parts of the norite body is clearly indicated. Both the shagreen orthoclase and the micropegmatite, as well as some interstitial quartz, are largely developed in the norite of the quarry on the Croton reservoir. The probability that they were introduced in solution when the norite was already solid is increased by the presence of veins of quartz-tourmaline pegmatite in the rock at this locality. Orthoclase and micropegmatite have not been found in hornblende norite or hornblende diorite, but only in augite norite.

PLAGIOCLASE

Rogers stated that the composition of the plagioclase in the diorites varies from oligoclase to andesine, but that it may be labradorite when the rock carries hypersthene. In the norites he referred especially to andesine and labradorite but mentioned oligoclase and bytownite in special instances. The norms computed from his analyses all show a small excess of anorthite over albite, yet there is a considerable amount

of orthoclase too and one has no means of judging how much of this is contained in the plagioclase. The only analysis of diorite shows more than three times as much anorthite as albite; but since the mode shows 32 per cent of biotite, whereas no corundum appears in the norm, it is clear that the proportion of lime and consequently that of anorthite has been overestimated by the analyst.

To study the variation in the composition of the plagioclase a large number of feldspars were examined on the universal stage. The results were often unsatisfactory on account of pressure phenomena such as wavy extinction, curved twinning lamellae, or an excessive number of thin and indistinct lamellae. This was particularly true of the dioritic rocks, for which it was necessary to supplement the universal method by simple measurement of extinction angles. The following results were obtained:

Hornblende norite	Average composition of plagioclase, An_{53}
	Range of composition, An_{47} to An_{60}.
Augite norite	Average composition of plagioclase, An_{52}
	Range of composition, An_{48} to An_{60}
Diorite	Average composition of plagioclase, An_{60}
	Range of composition, An_{48} to An_{72}
Average for all rocks examined, An_{59}	

The great majority of these feldspars were twinned on the albite-Carlsbad law; a few were acline or pericline twins. The only general deduction that it would be permissible to make from the data is that the hornblendic rocks have a slightly more calcic feldspar than those without hornblende.

AUGITE AND HYPERSTHENE

These minerals were described at length by Williams (1884, p. 263; 1887, p. 140) and by Rogers (p. 32, 41), and there is little to add to their descriptions. The pale greenish augite has an optic axial angle of $52° - 54°$; the extinction angle ($c \wedge X$) is $40° - 45°$. The presence of a small amount of enstatite in excess of the diopside formula is indicated.

The rhombic pyroxene was described by Rogers as enstatite, as bronzite, and as hypersthene in different cases. In every section examined by the writer this mineral shows such strong pleochroism that it could only be hypersthene. Even in the thinnest sections the change of color from pink to green is clearly seen when the stage is rotated. The universal stage confirms this conclusion, although it shows that the iron content of the mineral varies from one rock to another. The optical sign is always negative, and the axial angle ranges between 58° and 72°, corresponding to a molecular proportion of 30 to 45 per cent of ferrosilite.

Rogers noted that the hypersthene in the pyroxenites is less ferriferous than that in the norites. This seems to be supported by a few axial angle determinations which indicate $2V = 68° - 72°$, in the pyroxenitic hyper-

sthene, and also by Rogers' own chemical analyses. If we compare the molecular ratio of FeO : MgO in Rogers' analyses, having first deducted in each case enough FeO to form magnetite with all the Fe_2O_3 and ilmenite with all the TiO_2, we get the following result:

Name of rock	No. of analysis	Content of pyroxene	Adjusted ratio of FeO:MgO
		(Per cent)	
Leucocratic norite	5	13	2:3
Biotite norite	6	10	1:2
Biotite-augite norite	8	11	2:3
Hornblende norite	9	10	1:2
Pyroxenite	10	64	1:3.2
Olivine pyroxenite	11	65	1:6.2
Melanocratic norite	21	75	1:5

It seems to be demonstrated by these figures that in rocks with much pyroxene the pyroxene is more magnesian than it is in rocks with little pyroxene. Analyses No. 21 and No. 5 are particularly interesting because in each case hypersthene is the only dark mineral present. This result is what one might expect if the pyroxenites are products of crystal settling, since the early-formed pyroxenes would normally be more magnesian than those formed at a late stage.

In the presence of plagioclase the pyroxene grains are hypidiomorphic, but in pyroxenites and peridotites the grains are allotriomorphic, typically forming an even-grained mosaic. Normally each pyroxene is free from enclosures of the other, but in a few rocks, generally containing olivine, there are good examples of poikilitic hypersthene enclosing both augite and olivine.

GARNET AND EPIDOTE

These two minerals are confined to the margin of the complex. Garnet appears in the dioritic rocks at Crugers, and also across the river at Stony Point; in each case the schist near by is garnetiferous. It is found again west of Montrose, where a big mass of schist has been incorporated in diorite; and it is one of the commoner constituents of the ore bodies at the schist contact on Emery Hill. Epidote occurs in quantity in the dioritic rocks at Crugers and Stony Point but has not been found elsewhere; it was described by Williams (1884, p. 444).

Except as indicators of a certain degree of reaction between the magma and its walls, these phases convey little information about the cooling history of the magma.

HISTORY OF THE COMPLEX

With the data now available it seems possible for the first time to offer a reasonable outline of the history of the complex. It was assumed by Williams and by Rogers that the earliest magma was pyroxenitic and that it was followed by a noritic magma and a dioritic magma. This conclusion was based on the supposed "law of decreasing basicity" and little else. It is true that dioritic rocks may occasionally be seen to enclose or inject pyroxenite, but this is not enough to demonstrate successive intrusions of magma. Convection currents in a partly crystallized liquid might produce the same effect, thus there is no certainty that the pyroxenite was formed from an earlier magma than the other rocks.

D. L. Reynolds (1935, p. 472) has compared the Cortlandt complex to the Newry complex in northern Ireland, where she believes the parent magma to have been an ultrabasic one now represented by biotite pyroxenite and biotite peridotite. By the action of this magma and its alkaline emanations upon surrounding sedimentary rocks a series of hybrid rocks is thought to have been generated, ranging from diorite and monzonite to granodiorite. Professor Arthur Holmes has given full support to Dr. Reynolds' views and has stated positively (1937, p. 40) that in the Cortlandt complex "the ultrabasic types are parental and others are hybrids due to reaction with the alkali-enriched surrounding rocks."

Neither field nor laboratory evidence yields any support for this view. The dioritic and rare monzonitic rocks of the Cortlandt complex do indeed represent a somewhat contaminated magma, but it was a noritic magma, not a pyroxenitic one. Nothing is known that would indicate biotite pyroxenite or biotite peridotite as the parent of either norite or diorite in this region. Biotite is a very subordinate constituent of the pyroxenites and peridotites, and is believed to be entirely deuteric; that is, instead of the pyroxenites having given off alkali-rich emanations they seem to have received such emanations. To argue from Cortlandt to Newry would be just as unsatisfactory as to argue from Newry to Cortlandt; the writer would merely say that his examination of both areas has led him to think that the Newry pyroxenite played the same passive role as the Cortlandt pyroxenite—it did not act; it was acted upon.

The relation between pyroxenite and norite may be studied on a number of rather inadequate exposures in road cuts west of Salt Hill and northwest of Dickerson Hill. These exposures show bands of melanocratic norite alternating with bands of pyroxenite in such a way as to suggest contemporary rather than successive emplacement of the two kinds of rock. The evidence is somewhat vitiated by the growth of deuteric hornblende in both rocks, which has the effect of obscuring the junction between them;

but norite has not been seen to cut pyroxenite in such a way as to make it clear that the norite is younger, and no enclosures of pyroxenite have been observed in the norite. Both rocks contain the same two pyroxenes, with identical optical characters, and the pyroxenite holds little pools of plagioclase near its junction with norite. The rock exposed on the west side of Emery Hill was mapped as pyroxenite by Rogers, yet Butler showed that it may hold as much as 15 per cent of plagioclase. A narrow belt of pyroxenite always seems to intervene between norite and peridotite. As far as this evidence goes it indicates that norite and pyroxenite were formed from the same magma, which must of necessity have been a norite magma; and suggests that the formation of pyroxenite and peridotite took place by the settling of crystals out of this magma.

Since the total bulk of pyroxenite and peridotite, as judged by area, is more than one-third of the bulk of norite and diorite, the parent magma must either have been a very melanic one or else we must suppose that the higher levels of the complex, long since eroded away, contained a greater proportion of norite than the level now exposed. This assumption need not frighten us. A similar assumption on a much larger scale seems to be necessary in the case of the Great Dyke of Rhodesia.

The characteristic arrangement of steeply dipping parallel bands in the complex could scarcely have arisen during the ascent of the magma, but it might perhaps have been generated during a later subsidence of the partly differentiated mass of crystals and liquid, the central portion sinking more rapidly than the sides. (As a rude analogy, think of the shrinkage and central subsidence that take place in a precipitate of alumina or silica when left to drain in a filter funnel.) The writer is convinced of the reality of Balk's central funnel, but he feels some doubt about the suggested eastern and western funnels. Perhaps they are nodes rather than funnels.

When the last of the norite had solidified, it is necessary to suppose that steam or hot solutions rose (mainly) through the center of the mass in the funnel and brought about the reaction which generated the poikilitic brown hornblende. The coarse-grained bands were more permeable than the fine-grained ones, hence the solutions traveled and the process of hornblendization took place chiefly in the coarser bands and along cracks. The outline of the main region of poikilitic hornblende conforms therefore to the strike of the banding in the norite. About this time or very slightly later there was some development of biotite, chiefly in the augite norite but to some extent in the hornblende norite too. The local introduction of orthoclase and micropegmatite and the occasional injection of granitic veinlets brought this stage to an end.

The reaction that gave rise to the brown hornblende liberated a small amount of alumina and magnesia (with iron oxide), part of which was deposited on the spot as poikilitic aggregates of iron ore and spinel; but another part is thought to have been carried outwards along ill-defined channels, to be precipitated eventually about the walls of the intrusion, thus giving rise to—or at least contributing to—the emery deposits.

ACKNOWLEDGMENTS

For the purpose of this investigation the writer spent about 25 days in traversing the complex and collecting new material for study. In this he had the help of Mr. Felix Chayes as field assistant, and was also accompanied at times by Dr. E. N. Cameron. His thanks are due to both for their good company and willing assistance. About 150 specimens were collected for slicing, and large thin sections of superior quality were prepared from these by Mr. George Rev. The excellent microphotographs were made by Mr. Chayes. Professor Robert Balk kindly permitted the reproduction of his small structural map which appears as Figure 1.

REFERENCES CITED

Balk, R. (1927) *Die primäre Struktur des Noritmassivs von Peekskill am Hudson, nördlich New York,* Neues Jahrb. Min., Beilageband 57, p. 249.

—— (1937) *Structural behavior of igneous rocks,* Geol. Soc. Am., Mem. 5, p. 92, Fig. 33.

Bowen, N. L. (1922) *The behavior of inclusions in igneous magmas,* Jour. Geol., vol. 30, p. 551.

Butler, J. W. (1936) *Origin of the emery deposits near Peekskill, New York,* Am. Mineral., vol. 21, p. 537.

Gillson, J. L., and Kania, J. E. A. (1930) *Genesis of the emery deposits near Peekskill, New York,* Econ. Geol., vol. 25, p. 506.

Holmes, A. (1937) *The volcanic area of Bufumbira,* Geol. Survey Uganda, Mem. 3, pt. 2, p. 40.

Reynolds, D. L. (1934) *The eastern end of the Newry igneous complex,* Geol. Soc. London, Quart. Jour., vol. 90, p. 585.

—— (1935) *The genetic significance of biotite-pyroxenite and hornblendite,* Min. Pet. Mitt., vol. 46, p. 472.

Rogers, G. S. (1911) *Geology of the Cortlandt series and its emery deposits,* N. Y. Acad. Sci., Ann., vol. 21, p. 11.

Williams, G. H. (1884) *On the paramorphism of pyroxene to hornblende in rocks,* Am. Jour. Sci., 3d ser., vol. 28, p. 259.

—— (1886) *The peridotites of the Cortlandt series on the Hudson River near Peekskill,* Am. Jour. Sci., vol. 31, p. 26.

—— (1887) *The norites of the Cortlandt series on the Hudson River near Peekskill,* Am. Jour. Sci., 3d ser., vol. 33, p. 135, 191.

Williams, G. H. (1887) *On the chemical composition of the orthoclase in the Cortlandt norite,* Am. Jour. Sci., 3d ser., vol. 33, p. 243.

——— (1888) *The gabbros and diorites of the Cortlandt series on the Hudson River near Peekskill,* Am. Jour. Sci., 3d ser., vol. 35, p. 438.

COLUMBIA UNIVERSITY, NEW YORK, N. Y.
MANUSCRIPT RECEIVED BY THE SECRETARY OF THE SOCIETY, JUNE 30, 1941.
PRESENTED BEFORE THE SOCIETY, DECEMBER 28, 1940.

Topography after U. S. Geological Survey, West
rangle. Heavy line represents outer boundar
according to R. Balk.

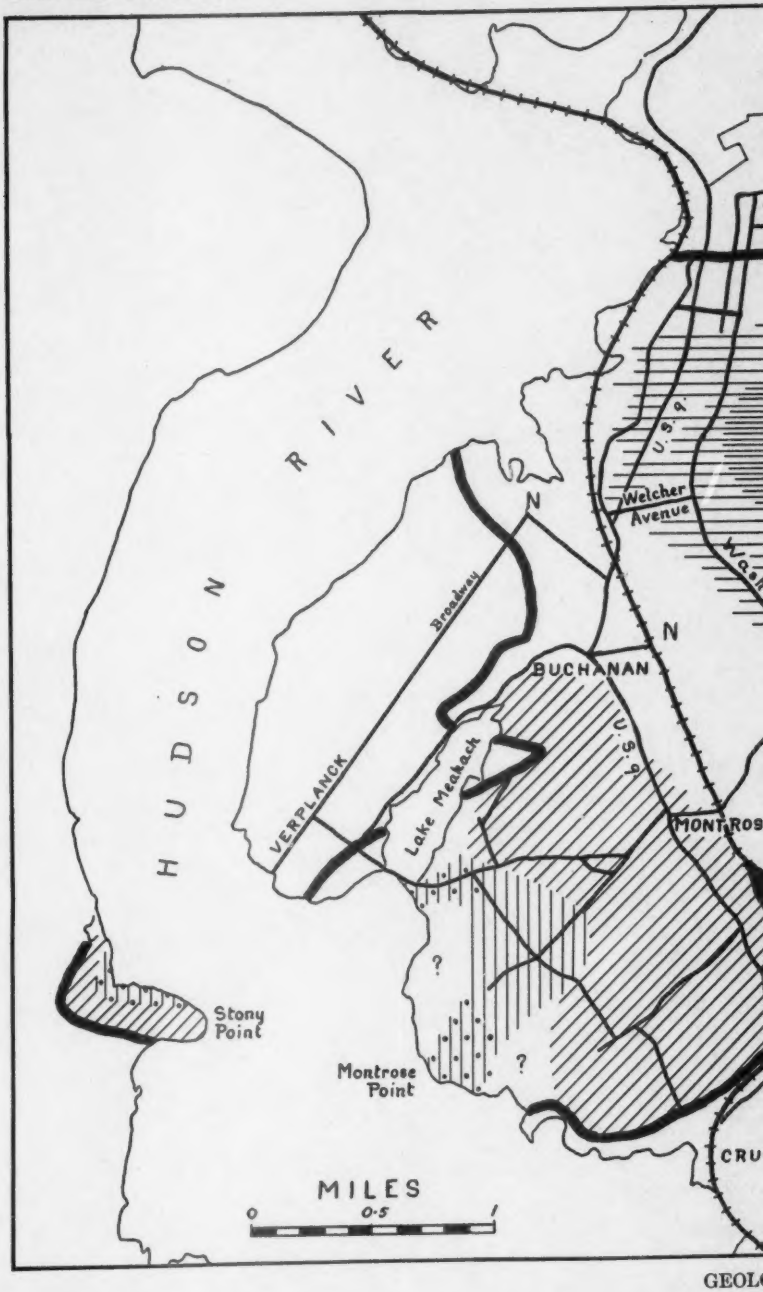
Region of poikilitic hornblende { hornblende sporadic / hornblende abundant

Region of prismatic hornblende.....

Olivine region .....

Pyroxenite (without olivine) .....

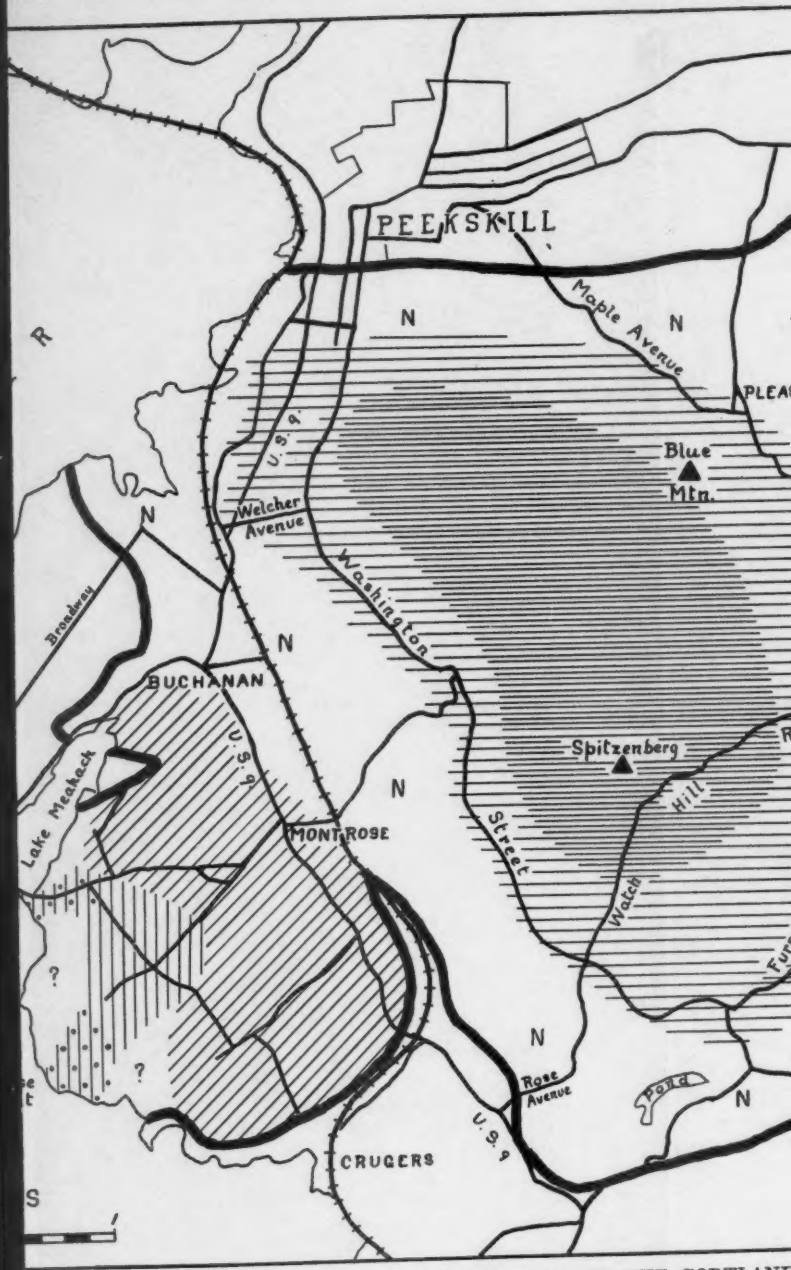
Augite norite (without hornblende).....



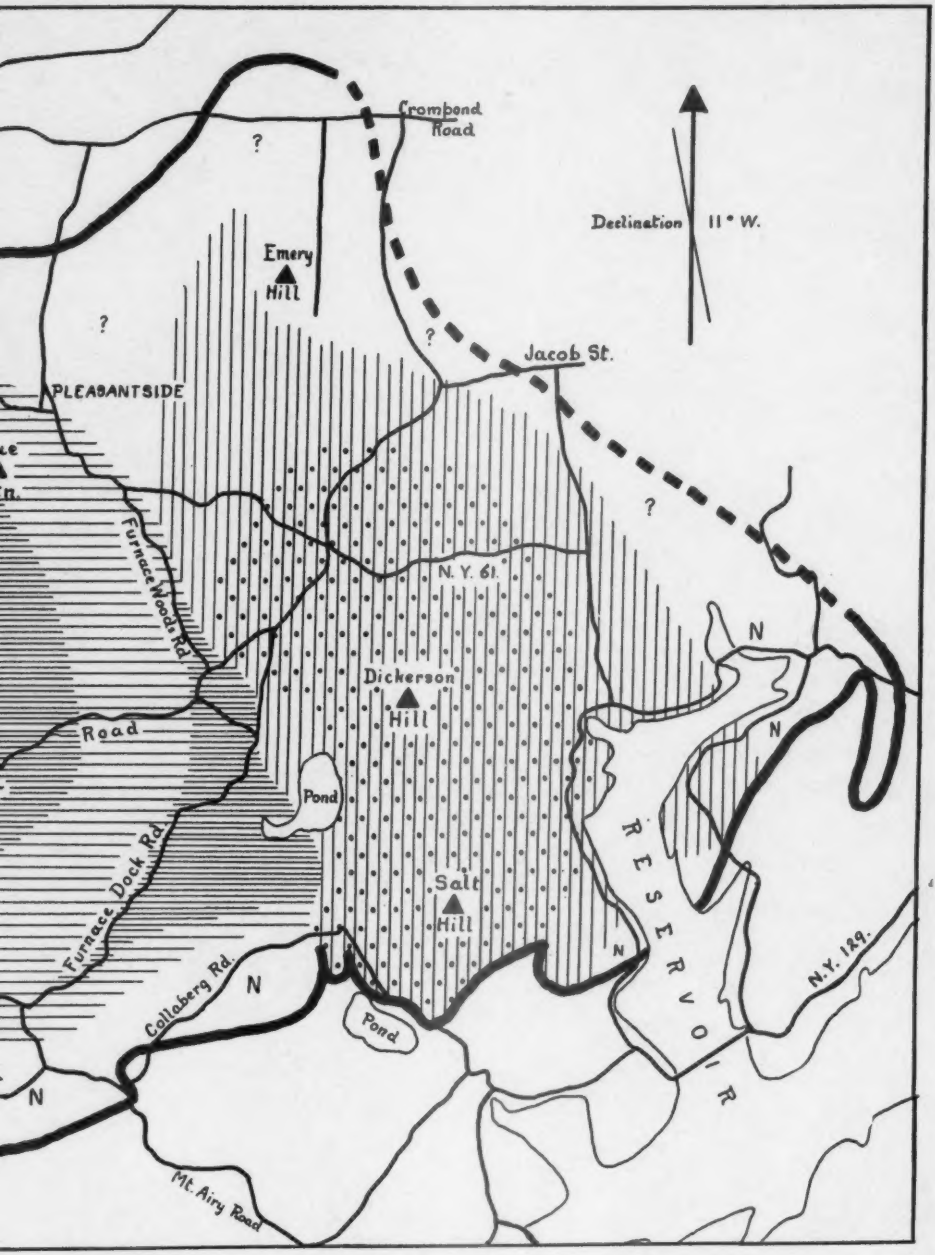
urvey, West Point quad-
ter boundary of complex

rnblende
sporadic
rnblende
abundant

N



GEOLOGICAL DIAGRAM OF THE CORTLAND



RTLANDT COMPLEX

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 53, PP. 429-434. MARCH 1, 1942

CORRELATION CHARTS PREPARED BY THE COMMITTEE ON STRATIGRAPHY OF THE NATIONAL RESEARCH COUNCIL

BY CARL O. DUNBAR *(Chairman)*, G. ARTHUR COOPER, CAREY CRONEIS, B. F. HOWELL, RAYMOND C. MOORE, JOHN B. REESIDE, JR., LLOYD W. STEPHENSON, CHARLES K. SWARTZ, W. H. TWENHOFEL, AND C. E. WEAVER.

With the collaboration of about 70 additional American stratigraphers

CONTENTS

	Page
Introduction	429
History of the project	430
Acknowledgments	431
Format	432
References cited	433

INTRODUCTION

The Committee on Stratigraphy of the National Research Council introduces herewith a series of 12 charts showing the classification and correlation of the post-Proterozoic sedimentary formations of North America. These charts have been under study and preparation for nearly 10 years and represent the combined efforts of a large group of American stratigraphers.

Since some of the charts are now completed, whereas others will require further preparation, the plan is to publish them individually as they are ready and without regard to stratigraphic order. Each chart, with several pages of annotations, will form an individual paper in the BULLETIN. The first of them follows in this issue. It is planned to publish a considerable number of reprints which may be purchased separately or in sets.

The complete set will include the following:

CHART No. 1. Cambrian Formations of North America, by B. F. Howell, *et al.*

CHART No. 2. Ordovician Formations of North America, by W. H. Twenhofel, *et al.*

CHART No. 3. Silurian Formations of North America, by C. K. Swartz, *et al.*

CHART No. 4. Devonian Formations of North America, by G. Arthur Cooper, *et al.*

CHART No. 5. Mississippian Formations of North America,
by Carey Croneis, *et al.*

CHART No. 6. Pennsylvanian Formations of North America,
by Raymond C. Moore, *et al.*

CHART No. 7. Permian Formations of North America,
by Carl O. Dunbar, *et al.*

CHART No. 8. Triassic and Jurassic Formations of North America,
by John B. Reeside, Jr., *et al.*

CHART No. 9. Cretaceous Formations of the Atlantic and Gulf Coastal Plain,
by Lloyd W. Stephenson, *et al.*

CHART No. 10. Cretaceous Formations of Western North America,
by John B. Reeside, Jr., *et al.*

CHART No. 11. Cenozoic Formations of Western North America,
by Charles E. Weaver, *et al.*

CHART No. 12. Cenozoic Formations of the Atlantic and Gulf Coastal Plain and the Caribbean Region,
by C. Wythe Cooke, *et al.*

HISTORY OF THE PROJECT

The Committee on Stratigraphy was inaugurated in 1932 through the initiative of W. H. Twenhofel, who was then chairman of the Division of Geology and Geography of the National Research Council. It was organized, after preliminary informal discussion, with 10 members, each a specialist in a distinct system, so that all parts of the geologic column would be represented. An organization meeting was held during the sessions of The Geological Society of America in Cambridge on December 29, 1932, and objectives and plans were discussed.

At that time the need of synthesis of existing knowledge of American stratigraphy was very great. Nearly 50 years had elapsed since the *Correlation Papers* of the United States Geological Survey were issued, and Willis' *Index to Stratigraphy* was out of print and 20 years out of date. Meanwhile, the constantly growing volume of stratigraphic literature exceeded the capacity of any individual to read and assimilate. It appeared evident, therefore, that only the combined efforts of a group of specialists could cover this vast field and adequately synthesize what is now known as to the classification and correlation of the sedimentary record.

Facing this goal, each of the 10 members of the committee undertook to organize a subcommittee to cover one distinct system. For this he invited the collaboration of several specialists in that part of the geologic column, so distributed geographically that, insofar as possible, one, at least, would be familiar with each important area of outcrop through actual field experience.

During 1933 these subcommittees were organized, and 81 American stratigraphers accepted the responsibility of contributing to this work. The committee of 10 met in Rochester on December 29, 1934, to compare preliminary results and discuss further development of the project. It was then decided as an immediate goal to prepare a set of comprehensive correlation charts, such as these now presented, and to follow this later with an adequate text in the form of a set of Handbooks on American Stratigraphy. The scope and format of the charts were discussed, and various details were agreed upon. A preliminary style sheet was distributed to all members in March 1935, and the charts have been under preparation since that time.

The long delay in completion of this project is due to a combination of factors. Foremost of these has been the difficulty of getting adequate data on many of the correlations. The very attempt to express graphically the relations of all the formations in each important area of outcrop at once focused attention on serious gaps in our knowledge. It was recognized, of course, that such difficulties could not all be solved and that vastly more fact finding must be done before the final correlation charts can be drawn. Nevertheless, many of the problems encountered could be solved or were being attacked by those actively interested. As a result, each chart, after preliminary drafting, has been held up for completion or revision as critical information became available. A large number of special studies has meanwhile been stimulated by the difficulties encountered in the preparation of the charts. During these years of study, each of the charts has been extensively revised, and several of them completely redrafted two or three times. It is hoped that the improvements thus achieved will more than justify the delay.

It must be emphasized, however, that these charts are no more than an attempt to express our present knowledge. Considerable parts of the stratigraphic record are still very imperfectly known, and future work will certainly indicate many corrections in the present correlations. It is hoped that the charts will be a challenge to every field worker and that needed corrections will be brought to the attention of the members of the committee so that they may be incorporated in a revision at some future date.

ACKNOWLEDGMENTS

The 10 members of the Committee on Stratigraphy acknowledge gratefully the indispensable aid of the many colleagues who, as members of the several subcommittees, have contributed to the preparation of the charts. Their names appear on the appropriate charts, as a part of the caption. In most of the charts, individual members are responsible for

the arrangement in particular columns, as indicated. However, each chart has been studied and freely criticized by the several members of the subcommittee concerned, and commonly by interested specialists outside the committee; final decisions were made by each contributor after consideration of such criticisms.

Many items of classification and of correlation are still controversial. Obviously, such scientific problems cannot be settled by a majority vote, and the committee has been anxious not to suppress reasonably qualified differences of opinion. In all controversial correlations it has been necessary to choose one of the alternative interpretations for use in the chart, but the opposed view is indicated by an annotation in the text.

Special thanks are also due the Director of the United States Geological Survey and the Director of the Geological Survey of Canada, both of whom have approved active co-operation of their respective organizations in this project.

One of the most important modern documents in American stratigraphy is a codification of good usage in matters of classification and stratigraphic nomenclature, which appeared in 1933 under the title *Classification and Nomenclature of Rock Units* (Ashley, *et al.*, 1933). It is the work of a committee of 14, representing the Association of State Geologists, the United States Geological Survey, the Association of Petroleum Geologists, and The Geological Society of America. The principles therein set forth have been adopted and applied by the committee with the exception of one item—namely, the use of the term *stage*. The *Code* recommends the use of *stage* as a time unit in the Pleistocene; but its original use by D'Orbigny was as a stratigraphic unit, and it has been consistently and widely used in that sense by European geologists. (*See*, for example, Arkell, 1933.) The majority of the committee believe it should be so used by Americans. It has been used thus on some, but not all, of the present charts.

The *Lexicon of Geologic Names* by M. Grace Wilmarth, published as United States Geological Survey Bulletin 896 in 1938, has been of great aid in the final completion of our charts, though it appeared after most of them had been drafted. It will be an indispensable corollary to the charts, however, since it gives critical bibliographic references and indicates the character and immediate stratigraphic relations of most of the formations represented thereon.

FORMAT

The charts are all cast in the same general format, with a generalized standard section at the left and a standard European section either at the left or the right; but some variations in details of style have been neces-

sary. In certain of the charts there is included in the generalized standard section a column showing the ranges of selected guide fossils (chiefly genera), but in others this has not been deemed feasible. Moreover, the actual differences in stratigraphic complexity, completeness of exposure, or structural complexity have required some differences in treatment in different parts of the geologic column.

In each chart, enough columns have been introduced to represent the chief areas of outcrop, and in areas involving important changes of facies enough columns are used to represent the complexity. In several instances, where space permits, stratigraphic diagrams are inserted to bring out complex relations.

An attempt has been made to arrange the columns in natural geographic sequence, but it has not been possible to follow a uniform arrangement because of differences in outcrop pattern and other stratigraphic relations.

Shading by vertical lines indicates a hiatus, and by oblique lines an interval in which the presence or absence of beds is undetermined. Where upper or lower limits of formations cannot be placed definitely, question marks are inserted in the boundary lines. Distinct facies of equivalent age are separated by zigzag lines symbolizing intertonguing. Numerals refer to correspondingly numbered annotations.

REFERENCES CITED

Arkell, W. J. (1933) *The Jurassic system in Great Britain*, p. 8-14.

Ashley, G. H., *et al.* (1933) *Classification and nomenclature of rock units*, Geol. Soc. Am., Bull., vol. 44, p. 423-459.

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Manuscript received by the Secretary of the Society, September 17, 1941.

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 53, PP. 435-448, 1 PL. MARCH 1, 1942

CORRELATION OF THE OUTCROPPING CRETACEOUS FORMATIONS OF THE ATLANTIC AND GULF COASTAL PLAIN AND TRANS-PECOS TEXAS

BY LLOYD W. STEPHENSON, PHILIP B. KING, WATSON H. MONROE, AND RALPH W. IMLAY

CONTENTS

	Page
Introduction	435
Annotations	436
Upper Cretaceous	436
Lower Cretaceous	442
References cited	444
Explanation of red overprints	448

ILLUSTRATION

Plate	Facing page
1. Correlation of the outcropping formations of the Atlantic and Gulf Coastal Plain and trans-Pecos Texas (Chart 9 of series)	448

INTRODUCTION

This is Number 9 of a series of correlation charts prepared by the Committee on Stratigraphy of the National Research Council, which will cover the post-Proterozoic sedimentary formations of North America. For general information about the project the reader is referred to the general introduction preceding this paper.

The senior author, Lloyd W. Stephenson, is responsible for that part of the chart treating of the Upper Cretaceous series in the Atlantic and Gulf Coastal Plain (exceptions noted below) and the Lower Cretaceous series of the North Atlantic Coastal Plain; with respect to the Upper Cretaceous his presentation is based largely on his personal knowledge of the paleontology and stratigraphy of the area, gained from field and laboratory studies ranging from reconnaissance to detailed; all published information has been considered, and much of it utilized, but it is not practicable to include a complete bibliography. References are given to papers presenting views differing from those of the author, and to recent papers not yet listed in bibliographies. A complete bibliography of Texas geology through 1932 is given by Sellards (1933, p. 819-965). Watson H. Monroe has collaborated in the preparation of that part of the chart showing the

relations of the Upper Cretaceous units in Alabama and Mississippi. The classification shown in the Upper Cretaceous part of the Delaware column is based on a recently published paper by Charles W. Carter (1937, p. 237-281). Philip B. King is responsible for the remainder of the chart covering the Lower Cretaceous (Comanche series) of central Texas (largely compiled from published sources) and all of the Cretaceous in trans-Pecos Texas (from personal knowledge and published sources). In March 1941 this part of the chart was checked by R. W. Imlay, and changes were made by King at his suggestion. References to the more important literature are given.

In a correlation chart of this kind, in which age equivalencies are expressed by horizontal lining, it is obviously impossible to indicate relative thicknesses by vertical spacing. Hiatuses are indicated by vertical lining. The red-line overprint is intended to indicate certain important lithologic and faunal boundaries, and to assist the eye in recognizing the age relationships of the geologic units.

ANNOTATIONS

UPPER CRETACEOUS

1. The annotations are numbered to correspond with the numerals on the chart.

2. In the Upper Cretaceous series there are considerable lateral differences in thickness in beds of the same age. The series has its fullest development in the latitude of the region between Grayson and McLennan counties, Texas; there is in general a thinning of the series from 3000 feet or more in this region to less than 500 feet in New Jersey. This thinning may be due in part to the cessation of deposition from time to time, now manifested in the sediments as diastems and unconformities, in part to the removal of material by erosion during periods of emergence, and in part to the deposition of greater quantities of material in the Gulf region than in the North Atlantic region while the series was in process of accumulation. The magnitude of the hiatuses represented by some of the unconformities has not been determined with any degree of accuracy.

The absence of sharply defined faunal zones of regional extent in some parts of the series and lack of knowledge as to the number and vertical distribution of the diastems and unconformities have rendered difficult the accurate vertical placing of some of the recognized lithologic units; this difficulty has been experienced especially in the North Atlantic Coastal Plain and in the Chattahoochee region.

3. An Upper Cretaceous section similar to that in the Chisos and Terlingua areas is found farther northwest in trans-Pecos Texas in the Sierra Tierra Vieja, near the old San Carlos coal field. The Upper Cretaceous

beds of this region, from the base of the Tertiary volcanics down to the base of the exposed section, have been called the San Carlos formation by Vaughan (1900a, p. 81). Adkins has, however, divided it into a number of units, recognizing the Tornillo, Aguja, and Terlingua formations as in the Chisos and Terlingua areas, but calling the marls and limestone flags of Austin age the Colquitt formation and the clays of Eagle Ford age the Chispa Summit formation.

On the northeast slope of the Davis Mountains about 50 miles west of Fort Stockton a section of Upper Cretaceous rocks includes beds of Taylor age at the top. Elsewhere in trans-Pecos Texas the highest Upper Cretaceous beds are of Eagle Ford or Austin age.

4. Fossils of upper Taylor age have been identified from beds referred to the lower part of the Aguja formation. One lot of oysters reported to be from beds of this stratigraphic position consists of the shells of *Ostrea cortex* Conrad, a species that in Maverick and other counties to the eastward is known only from the Escondido formation (upper part of Navarro group); if its stratigraphic position is correctly reported the presence of this oyster in the Aguja formation indicates that it has a lower stratigraphic range in west Texas than it has in Maverick County.

5. Adkins treats the Eagle Ford unit as a group and, from notes of W. L. Moreman, quotes the descriptions of three proposed formational divisions, from below upward, the "Tarrant sandy clay and limestone," the "Britton clay," and the "Arcadia Park shale."

The dark clay unit intervening between the Grayson marl below and the Eagle Ford shale above, that Adkins called Pepper clay (1933, p. 417), and which he referred provisionally to his Woodbine group, is in this chart included in the Eagle Ford shale; the stratigraphic position of this clay has not been established.

6. Adkins (1933, p. 449-451) proposed the formation name Burditt marl for the upper 40 or 50 feet of the Austin chalk, part of which in the Little Walnut Creek section, Travis County, is softer and more marly than the more typical beds below. These softer beds are, however, no more marly than beds in the middle and lower parts of the formation in other parts of Texas, and Stephenson (1937, p. 133-136) has recently presented paleontologic and stratigraphic reasons for regarding Adkins' Burditt as of no higher rank than that of member of the Austin chalk, if, indeed, it seems necessary to recognize it as a separate unit at all. In the same paper Stephenson (1937, Fig. 7, p. 135; p. 139-140) includes in the Austin the Gober tongue of northeastern Texas, the upper part of which is even younger and stratigraphically higher than Adkins' Burditt marl; he recognizes an important regional unconformity between the Austin chalk and the overlying Taylor marl.

7. Adkins (1933, p. 434-436) interprets this 2-foot bed at the top of the Eagle Ford shale in Travis County as a so-called condensed zone containing a mixture of fossils from at least five upper Eagle Ford zones, brought together in consequence of the extremely slow deposition of sediments in a shallow, clear sea during a long period. Although theoretically possible, this condition can hardly be accepted as an established fact on the available published evidence; more information is needed as to the geologic ranges of the genera listed as occurring together in this bed.

8. Stephenson has observed that the Corsicana marl is absent in exposures along a small branch of Mustang Creek 3 miles south-southwest of Thrall, 1 mile west-southwest of Noack, Williamson County. Here a soft, earthy, cream-colored limestone 4 to 6 inches thick lies at the base of the Kemp clay and rests unconformably upon uppermost Taylor marl; abundant phosphatic material is present in the basal few inches of the limestone.

9. The Taylor marl and its age equivalents in the Atlantic and Gulf Coastal Plain are coextensive with all but the lowermost part of the major faunal zone known as the *Exogyra ponderosa* zone. It is possible to subdivide this zone species into several varieties that are of subzonal value within the larger zone, but this has not as yet been formally done.

10. The Navarro group, formerly classed as a formation, has been subdivided into four formations in Navarro, Kaufman, and Hunt counties, where it has its fullest development; these units are, in ascending order, Neylandville marl, Nacatoch sand, Corsicana marl, and Kemp clay. This classification was first suggested by Stephenson (Adkins, 1933, p. 516) and was adopted for the new geologic map of Texas issued by the U. S. Geological Survey in 1937. (*See also* Stephenson and Monroe, 1937, p. 809; Stephenson, 1941a, p. 637-643; 1941b.)

The Navarro group and its equivalents are coextensive with the *Exogyra costata* zone, a major faunal zone extending from New Jersey to the Rio Grande and beyond into Mexico. The species *Exogyra cancellata* Stephenson is restricted to the lower part of the *costata* zone and forms a much narrower zone having the same linear extent as the larger zone; in Texas the Neylandville marl, the lowermost formation of the Navarro group, is coextensive with the *cancellata* zone. In the opinion of several micropaleontologists, notably Dr. Joseph A. Cushman and Mrs. F. B. Plummer (oral communications), the microfauna carried by the *cancellata* zone in the Gulf region is definitely more closely related to that of the Taylor marl below than to that of the Navarro group above; they find an important faunal break between the Neylandville marl and the Nacatoch sand above, but none between the Neylandville and the Taylor marl below. To them the top of the Neylandville seems the logical place to draw the

boundary between the Taylor and the Navarro. On the contrary the molluscan fauna of the *cancellata* zone seems more closely allied to the younger faunas above than it does to the older faunas below; this is particularly true of the fine assemblage of mollusks described by Wade (1926) from the Coon Creek tongue of the Ripley formation in McNairy County, Tennessee, which forms the upper part of the *cancellata* zone. The *Exogyra ponderosa* and *Exogyra costata* zones have been recognized for years as major faunal zones in the Upper Cretaceous, and the Taylor marl was by original definition the *"Ponderosa"* marl. Although not a conclusive argument, the latter is cited as an additional reason for assigning the Neylandville marl to the Navarro group, for it lies above the upper range of *Exogyra ponderosa*. It is suggested that the microfaunal difference between the Neylandville and Nacatoch may be mainly a facies difference.

In Delaware and New Jersey, *Exogyra cancellata* is known only in the Mount Laurel sand, the lowermost formation of the Monmouth group, and this formation carries a microfauna which, according to Jennings (1936, p. 4-11, volume pages 162-169), is of lower Navarro age.

11. The Eagle Ford shale in Texas is separated from the underlying Woodbine sand by an unconformity. Compared with the European section the age of the Eagle Ford shale in its entirety was for many years accepted as Turonian; however, the basal beds of the formation, carrying the ammonite genus *Acanthoceras* and several other distinctive ammonite genera, are now considered to be Cenomanian. No unconformity has been recognized between these lower beds of Cenomanian age and the overlying beds of Turonian age, which make up the main body of the formation.

No representative of the Eagle Ford has been authentically recognized in surface outcrops in the Coastal Plain between the eastern boundary of Texas and New Jersey. Accepting E. W. Berry's correlation of the Tuscaloosa formation of the eastern Gulf region (1919a, p. 220-222, 341; 1919b, p. 41), with the Woodbine formation of Texas, which is known from its ammonite fauna to be of Cenomanian age, Stephenson and Monroe (1938, p. 1641, Fig. 2) have thought that the Eagle Ford is represented in the eastern Gulf region by the unconformity separating the Tuscaloosa from the overlying Eutaw formation. However, most of the Tuscaloosa plants have been found in the lower part of the formation, and the possibility that the middle and upper parts of the formation may include representatives of the Eagle Ford is recognized.

12. The Woodbine sand, as was recognized by R. T. Hill in his early writings, is separated from the underlying Washita group of the Comanche series by an unconformity. Few if any species of fossil organisms are known to range from the Washita group into the Woodbine sand, but the

lithologic facies of the two divisions are quite different, the former being composed of deeper, clearer-water sediments than the latter. Considerable difference of opinion exists as to the magnitude of the hiatus represented by this unconformity; if the contention of several authorities that the upper part of the underlying Washita group is of Cenomanian age is correct, the break cannot be of major importance, for there is a consensus of opinion that the Woodbine sand is also Cenomanian. The occurrence of the closely related genera of ammonities, *Engonoceras* and *Epengonoceras*, below and above the unconformity tends to confirm the view that the hiatus is not wide. The magnitude of the hiatus between the Washita and Woodbine increases from the latitude of Dallas southward, for the Woodbine sand thins out and disappears in that direction, beyond which, from Bell County southward, the Eagle Ford shale rests directly upon the Washita. This statement will need modification if the Pepper clay of Adkins is found to be older than Eagle Ford.

Subdivisions of the Woodbine sand are discussed by Adkins (1933, p. 408-422).

13. The evidence for the stratigraphic position of the Annona chalk, Pecan Gap chalk, and other units of Taylor age in Red River and adjacent counties, Texas, and in Arkansas, as expressed in this chart, is given by Stephenson (1937, p. 135, 139-144). A different interpretation is given by Ellisor and Teagle (1934, p. 1528-1533).

14. Exception has been taken by W. C. Spooner (1935, p. 86) to the assignment of these shallow-water deposits in southwestern Arkansas, including water-laid volcanic debris, to the Woodbine sand; he believes that they are at least in part younger than typical Woodbine. Field observations have shown, however, that beds of volcanic detritus in Lamar County, Texas, which are believed to represent the westward extension of the similar beds in Arkansas, definitely underlie lower Eagle Ford shale, and the volcanic beds pass to the westward in Fannin County beneath beds carrying an upper Woodbine (Lewisville) fauna. R. T. Hazzard (1939, p. 133-151) has also considered the tuffaceous beds of Arkansas as of Eagle Ford age.

15. The Coffee sand, previously classed as a member of the Eutaw formation on the basis of lithologic similarity, overlies the Tombigbee sand member of the Eutaw formation in northern Mississippi. Inasmuch as the Tombigbee member serves as a separating unit between the typical Eutaw beds below and the Coffee sand above, as far north as the place where both the typical Eutaw and the Tombigbee feather out against the Paleozoic rocks near the Mississippi-Tennessee State line, and inasmuch as the Coffee sand is of the age of the lower part of the Selma chalk, it simplifies the classification to treat the Coffee sand as a unit of formation

rank. This procedure was adopted by Stephenson (1939, p. 543, Pl. 3).

16. The application of the name Prairie Bluff chalk, previously regarded as an eastward-extending tongue at the top of the Selma chalk in central Alabama, has recently been extended by Stephenson and Monroe (1937, p. 806-809) westward through Alabama into Mississippi with formation rank, to include the upper 50 feet more or less of the Selma chalk, and the Oktibbeha tongue (abandoned) of the Selma, of previous classifications. The Prairie Bluff chalk merges northward in Mississippi into the nonchalky Owl Creek formation, a unit recognized by Stephenson and Monroe as separate from the Ripley formation proper. The Owl Creek is overlapped and concealed in Tennessee, Kentucky, and southern Illinois by the Porters Creek clay (Midway, Paleocene) but reappears again in Crowleys Ridge in southeastern Missouri. Evidence for the presence of the Owl Creek in Missouri is presented by Stephenson (*in* Matthes, 1933, p. 1003-1009; *in* Farrar, 1936, p. 17-20).

Paleontologic evidence has been accumulating to show that the lower part of the Prairie Bluff chalk and its equivalent, the Owl Creek formation, are synchronous with the Corsicana marl of Texas. The presence of the foraminiferal species, *Siphogenerinoides plummeri* Cushman, in the upper part of the Prairie Bluff chalk is interpreted by J. A. Cushman and Helen Jeanne Plummer (oral communications) to indicate the upper Kemp age of the containing beds. If this correlation is correct it would appear that the 50 feet or more of Prairie Bluff chalk represents the 400 feet or more of sediments composing the combined Corsicana marl and Kemp clay in Texas; as an alternative it is suggested that *S. plummeri* may have a longer vertical range than that assumed by the authorities cited.

17. The presence of an unconformity between the Tuscaloosa formation and the overlying Eutaw formation in eastern Alabama has been known for many years; recent investigations by Stephenson and Monroe have shown the extension of this unconformity westward across the State and northward through Mississippi in the Gulf Embayment, with probable increasing magnitude of the hiatus in that direction. This is contrary to the previous opinion of Stephenson that the gravels of the Tuscaloosa formation in northern Alabama, Tennessee, and Kentucky are basal gravels of the successively younger marine formations of the Gulf series in the Gulf Embayment area.

18. Upper Cretaceous fossils dredged from Georges Bank and Banquereau have been described as follows: Vermes, Echinodermata, and Mollusca, by Stephenson (1936, p. 367-410, Pls. 1-5); Bryozoa, by Bassler (1936, p. 411-412, Pl. 1, fig. 18); Foraminifera, by Cushman (1936, p. 413-440, Pls. 1-5). The geology of the Georges Bank canyons is described by Stetson in the same volume (1936, p. 339-366).

LOWER CRETACEOUS

19. In publications of the U. S. Geological Survey the Comanche series has always been classified as Lower Cretaceous, as a matter of convenience, although it has long been recognized that in its upper part it includes rocks that are probably younger (Cenomanian) than any assigned to the Lower Cretaceous in Europe.

20. The zone fossils for the Lower Cretaceous have been selected by R. W. Imlay on the basis of all information available to him in 1941. The list is not complete, and for further information the reader is referred to W. S. Adkins (1928).

21. References: R. W. Burrows, Geology of northern Mexico (1910, p. 85-103); W. S. Adkins (1933, p. 291-295).

22. The mountain ranges south of Sierra Blanca include Malone Mountain, the Quitman Mountains, Devil Ridge, and Eagle Mountain. Most of these consist of Mesozoic sedimentary rocks and include the oldest Cretaceous beds exposed in Texas. The structure of the rocks is very complex, and until recently the section has been poorly known. Work on the stratigraphy and structure is now in progress by C. C. Albritton, Jr., J. Fred Smith, Jr., Gayle Scott, and others, and a more comprehensive description of the section and its nomenclature will be available within a few years. At the present stage of knowledge, the sequence can only be indicated in general terms.

References: J. A. Taff, Cretaceous of El Paso County (1891, p. 714-738); T. W. Stanton, Stratigraphic notes on Malone Mountain (1905, p. 23-33); C. C. Albritton, Jr., Stratigraphy and structure of the Malone Mountains (1938, p. 1747-1806); J. Fred Smith, Jr., Stratigraphy and structure of the Devil Ridge area, Texas (1940, p. 597-638); Gayle Scott, Cephalopods from the Cretaceous Trinity group of the south-central United States (1940, p. 977-979); R. M. Huffington (1941, p. 1908).

23. References: J. A. Udden, Shafter district (1904). J. A. Udden, Chisos County (1907).

24. Reference: P. B. King, Geology of Glass Mountains (1931).

25. Reference: W. S. Adkins, Fort Stockton quadrangle (1927).

26. Reference: G. B. Richardson, Reconnaissance in trans-Pecos Texas north of Texas and Pacific railway (1904).

27. Reference: W. S. Adkins, Mesozoic systems, in The geology of Texas (1933, p. 353-355).

28. References: R. T. Hill and T. W. Vaughan, Nueces folio (1898). T. W. Vaughan, Uvalde folio (1900b).

29. The Georgetown limestone is thinner than its equivalents in northern Texas, which suggests the possibility that not all of the Washita formations or members of north Texas were deposited farther south.

According to Imlay, there is no evidence of unconformities between the Fort Worth and Main Street equivalents. Instead, "the reduced thickness of Fort Worth and overlying Washita beds in the area of the San Marcos arch is more probably due to lesser deposition than in areas away from the arch."

30. Adkins quotes F. L. Whitney as saying that near New Braunfels beds of Fort Worth age in the Georgetown limestone rest directly on the Edwards limestone. Imlay confirms this statement, as Whitney showed him a number of places in Comal County where the Fort Worth or even younger Washita beds rest directly on the Edwards limestone, whose upper surface beneath the Washita beds has a relief comparable with the present relief of the county.

31. The stratigraphic relations in the Fredericksburg group have been variously interpreted. There seems to be good evidence that the three formations of central Texas (Walnut, Comanche Peak, and Edwards) and the two of north Texas (Walnut and Goodland) are lithologic and faunal facies that replace each other laterally along the strike. These relations have been discussed in most detail by S. A. Thompson, and his interpretation is essentially that adopted on the chart. Adkins states that the units in the Fredericksburg are not true formations, and Thompson proposes to reduce them to the rank of members in a new formation (his Gatesville). These conceptions seem to be based on the idea that formations and zones or stages are the same, which is not the principle generally followed in the United States, as expressed in the code (Ashley et al., 1933, especially sec. 2, p. 430-432).

32. Reference: E. H. Sellards, Geology of Bexar County (1920).

33. Adkins and Cuyler both report that the Pawpaw is absent from central Texas. According to T. W. Stanton, however, "The Pawpaw is a local littoral facies which may be contemporary with quite different deposits (and fossils) elsewhere," a conclusion with which Imlay agrees.

34. Adkins and Cuyler both report that the Denton is greatly thinned in central Texas.

35. Adkins and others describe a thinning out of the Kiamichi toward the south and its entire disappearance in central Texas south of Coryell County.

36. References: R. T. Hill and T. W. Vaughan, Austin folio (1902); R. H. Cuyler, Georgetown formation of central Texas (1929, p. 1291-1299).

37. In a paper read before The Geological Society of America (Cincinnati meeting, 1936), R. T. Hill (1937, p. 79-80) interprets the Paluxy sand as the beginning of a cycle of sedimentation and suggests that it should therefore be classed as the basal unit of the Fredericksburg group.

38. References: W. S. Adkins, Geology of McLennan County (1923); W. S. Adkins, Geology of Bell County (1930); S. A. Thompson, The Fredericksburg group of the Lower Cretaceous (1935, p. 1508-1537).

39. Adkins presents evidence that the Grayson and Del Rio units are identical and proposes to use the name Grayson for all beds that have been previously called Del Rio. There seems to be some question, however, as to whether equivalents of the Buda limestone that overlies the Del Rio might not be present in the Grayson. In Denton County and elsewhere ledges or lenses of Buda-like limestone have been reported from the upper part of the Grayson and may be of Buda age. According to Adkins (1933, p. 397-398), "These contain high Washita fossils, but so far, nothing conclusively Buda has been reported from them."

40. Evidences of an unconformity at this level in Grayson County have been reported by L. W. Stephenson.

41. S. A. Thompson suggests that the Kiamichi lies unconformably beneath the younger Comanche deposits; he extends the unconformity even into north Texas, where the section is seemingly more complete.

42. Adkins, Thompson, and others class the Kiamichi with the Fredericksburg rather than with the Washita, which was the original interpretation. The newer interpretation is considered to harmonize better with the ranges of certain ammonoids and other fossils.

43. Thompson interprets the base of the Fredericksburg in north Texas as overlapping unconformably on the preceding Trinity beds. This usage is adopted on the chart. However, Adkins (1933, p. 325, Fig. 19) suggests that the basal sands in the north are younger than in the south and that they partly replace Fredericksburg, instead of being wholly of Trinity age. This interpretation is also followed by Stanton. Further proof is needed to sustain either interpretation. The Fredericksburg group is markedly thinner in north Texas than in central Texas, so either one interpretation or the other would seem to be necessary.

44. References: L. W. Stephenson, Northeast Texas and southern Oklahoma (1918); W. M. Winton and W. S. Adkins, Geology of Tarrant County (1919).

45. References: J. A. Taff, Tishomingo folio (1903); J. A. Taff, Atoka folio (1902); F. A. Bullard, Geology of Love County (1925).

46. Reference: R. W. Imlay, Lower Cretaceous and Jurassic formations of southern Arkansas and their oil and gas possibilities (1940).

REFERENCES CITED

Adkins, W. S. (1923) *Geology of McLennan County*, Univ. Texas, Bull. 2340, 202 pages, 4 plates.

Adkins, W. S. (1927) *The geology and mineral resources of the Fort Stockton quadrangle,* Univ. Texas, Bull. 2738, 166 pages, 6 plates.

—— (1928) *Handbook of Texas Cretaceous fossils,* Univ. Texas, Bull. 2838, 385 pages, 37 plates.

—— (1930) *Geology of Bell County, Texas,* Univ. Texas, Bull. 3016, 92 pages, 1 plate.

—— (1933) *The Mesozoic systems in Texas,* Univ. Texas, Bull. 3232, pt. 2, p. 239-518.

Albritton, C. C., Jr. (1938) *Stratigraphy and structure of the Malone Mountains, Texas,* Geol. Soc. Am., Bull., vol. 49, p. 1747-1806.

Ashley, G. H., *et al.* (1933) *Classification and nomenclature of rock units,* Geol. Soc. Am., Bull., vol. 44, p. 423-459.

Bassler, R. S. (1936) *Cretaceous bryozoan from Georges Bank,* Geol. Soc. Am., Bull., vol. 47, p. 411-412, pl. 1, fig. 18.

Berry, Edward Wilber (1919a) *The Upper Cretaceous floras of the world,* Md. Geol. Survey, Upper Cretaceous, p. 183-313.

—— (1919b) *Upper Cretaceous floras of the eastern Gulf region in Tennessee, Mississippi, Alabama, and Georgia,* U. S. Geol. Survey, Prof. Paper 112, 177 pages, 33 plates.

Bullard, F. A. (1925) *Geology of Love County, Oklahoma,* Okla. Geol. Survey, Bull. 33, 77 pages, 29 plates.

Burrows, R. H. (1910) *Geology of Northern Mexico,* Soc. Geol. Mexicana, bol., tome 7, p. 85-103, pl. 12.

Carter, Charles W. (1937) *The Upper Cretaceous deposits of the Chesapeake and Delaware Canal of Maryland and Delaware,* Md. Geol. Survey, vol. 13, pt. 6, p. 237-281, pls. 42-46.

Cushman, Joseph H. (1936) *Cretaceous and late Tertiary Foraminifera* [*Georges Bank*], Geol. Soc. Am., Bull., vol. 47, p. 413-440, 5 plates.

Cuyler, R. H. (1929) *Georgetown formation of central Texas,* Am. Assoc. Petrol. Geol., Bull., vol. 13, no. 10, p. 1291-1299.

Ellisor, Alva C., and Teagle, John (1934) *Correlation of Pecan Gap chalk in Texas,* Am. Assoc. Petrol. Geol., Bull., vol. 18, no. 11, p. 1506-1536.

Farrar, Willard (1936) *The Cretaceous and Tertiary geology,* Bienn. Rept. State Geol. [Missouri], 1935, Appendix 1, p. 17-20.

Hazzard, Roy T. (1939) *The Centerpoint volcanics of southwest Arkansas, a facies of the Eagle Ford of northeast Texas,* 14th Ann. Field Trip, Shreveport Geological Society, Guidebook, p. 133-151, 3 plates.

Hill, R. T. (1937) *Paluxy sands, with further notes on the Comanche series* (Abstract), Geol. Soc. Am., Pr. 1936, p. 79-80.

——, and Vaughan, T. W. (1898) *Nueces folio,* U. S. Geol. Survey, Atlas, no. 42, text, maps, and illustrations.

—— — —— (1902) *Austin folio,* U. S. Geol. Survey, Atlas no. 76, 8 pages, maps, illustrations.

Huffington, R. M. (1941) *Stratigraphy and structure of the northern Quitman Mountain area, trans-Pecos Texas* [Abstract], Geol. Soc. Am., Bull., vol. 52, p. 1908.

Imlay, R. W. (1940) *Lower Cretaceous and Jurassic formations of southern Arkansas and their oil and gas possibilities,* Ark. Geol. Survey, Inform. Cir. 12, 64 pages, 26 plates.

Jennings, Philip H. (1936) *A microfauna from the Monmouth and basal Rancocas groups of New Jersey,* Bull. Am. Paleont., vol. 23, no. 78, 76 pages, 7 plates (volume pages 159-234).

King, Philip B. (1931) *The geology of the Glass Mountains, Texas,* Univ. Texas, Bull. 3038, 245 pages, 15 plates, and geologic map.

Matthes, F. E. (1933) *Cretaceous sediments in Crowleys Ridge, southeastern Missouri,* Am. Assoc. Petrol. Geol., Bull., vol. 17, no. 8, p. 1003-1009.

Monroe, Watson H. (1942) *Notes on deposits of Selma and Ripley age in Alabama,* Ala. Geol. Survey, Bull. 48, 150 pages, 2 plates.

Richardson, G. B. (1904) *Reconnaissance in trans-Pecos Texas north of Texas and Pacific Railway,* Univ. Texas, Bull. 23, 119 pages, 11 plates. (The title page also indicates this paper as "Univ. of Texas, Min. Survey, Bull. no. 9.)

Scott, Gayle (1940) *Cephalopods from the Cretaceous Trinity group of the south-central United States,* Univ. Texas, Bull. 3945, p. 969-1106, pls. 55-68.

Sellards, E. H. (1920) *Geology of Bexar County,* Univ. Texas, Bull. 1932, 202 pages, 1 plate, and 1 geologic map.

——— (1933) *Bibliography and subject index of Texas geology,* Univ. Texas, Pub. no. 3232, p. 819-996.

Smith, J. Fred, Jr. (1940) *Stratigraphy and structure of the Devil Ridge area, Texas,* Geol. Soc. Am., Bull., vol. 51, p. 597-638.

Spooner, W. C. (1935) *Oil and gas geology of the Coastal Plain in Arkansas,* Ark. Geol. Survey, Bull. 2, 516 pages, 22 plates. (App. pls. 1A-4A.)

Stanton, T. W. (1905) *Stratigraphic notes on Malone Mountains and the surrounding region near Sierra Blanca, Texas,* U. S. Geol. Survey, Bull. 266, p. 23-33.

Stephenson, Lloyd William (1918) *A contribution to the geology of northeastern Texas and southern Oklahoma,* U. S. Geol. Survey, Prof. Paper 120-H, p. 129-163, pls. 17-30.

——— (1936) *Upper Cretaceous fossils from Georges Bank canyons,* Geol. Soc. Am., Bull., vol. 47, p. 367-410, 5 plates.

——— (1937) *Stratigraphic relations of the Austin, Taylor, and equivalent formations in Texas,* U. S. Geol. Survey, Prof. Paper 186-G, p. 133-146, pl. 44.

——— (1939) *Cretaceous system,* Geologie der Erde; Geology of North America—The Atlantic and Gulf Coastal Plain, p. 519-549, 4 plates.

——— (1941a) *Summary of faunal studies of Navarro group of Texas,* Am. Assoc. Petrol. Geol., Bull., vol. 25, no. 4, p. 637-643.

——— (1941b) *The larger invertebrate fossils of the Navarro group of Texas,* Univ. Texas, Pub. 4101, 641 pages, 95 plates.

———. and Monroe, Watson H. (1937) *Prairie Bluff chalk and Owl Creek formation of eastern Gulf region,* Am. Assoc. Petrol. Geol., Bull., vol. 21, no. 6, p. 806-809.

——— — ——— (1938) *Stratigraphy of Upper Cretaceous series in Mississippi and Alabama,* Am. Assoc. Petrol. Geol., Bull., vol. 22, no. 12, p. 1639-1657.

Stetson, Henry C. (1936) *Geology [Georges Bank canyons],* Geol. Soc. Am., Bull., vol. 47, p. 339-366, 3 plates.

Taff, J. A. (1891) *Cretaceous of El Paso County,* Texas Geol. Survey, Ann. Rept., vol. 2, p. 714-738.

——— (1902) *Atoka folio,* U. S. Geol. Survey, Atlas no. 79, 8 pages, maps.

——— (1903) *Tishomingo folio,* U. S. Geol. Survey, Atlas no. 98, 8 pages, maps.

Thompson, S. A. (1935) *The Fredericksburg group of the Lower Cretaceous,* Am. Assoc. Petrol. Geol., Bull., vol. 19, p. 1508-1537.

Udden, J. A. (1904) *The geology of the Shafter silver mine district,* Univ. Texas, Bull. 24, 60 pages. (The title page also indicates this paper as "Univ. of Texas, Min. Survey, Bull. no. 8.)

Udden, J. A. (1907) *A sketch of the geology of the Chisos country, Texas,* Univ. Texas, Bull., no. 93, 101 pages.

Vaughan, Thomas Wayland (1900a) *Reconnaissance in the Rio Grande coal fields of Texas,* U. S. Geol. Survey, Bull. 164, 100 pages, 11 plates.

——— (1900b) *Uvalde folio,* U. S. Geol. Survey, Atlas, no. 64, 7 pages, maps.

Wade, Bruce (1926) *The fauna of the Ripley formation on Coon Creek, Tennessee,* U. S. Geol. Survey, Prof. Paper 137, 272 pages, 72 plates.

Winton, W. M., and Adkins, W. S. (1919) *Geology of Tarrant County,* Univ. Texas, Bull. 1931, 122 pages, 6 plates, 1 geologic map.

U. S. Geological Survey, Washington, D. C.
Manuscript received by the Secretary of the Society, June 27, 1941.
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EXPLANATION OF RED-LINE OVERPRINTS

Red line *a*. Boundary between Prairie Bluff chalk, Owl Creek formation, Corsicana marl and beds of corresponding age, and older underlying formations.

Red line *b*. Top of *Exogyra cancellata* zone.

Red line *c*. Boundary between the *Exogyra ponderosa* and *Exogyra costata* zones; in Texas this is the boundary between the Taylor marl and the Navarro group.

Red line *d*. *Diploschiza cretacea* zone.

Red line *e*. Boundary between the Austin chalk and Taylor marl in Texas, and between beds of Austin and Taylor age in other parts of the Coastal Plain.

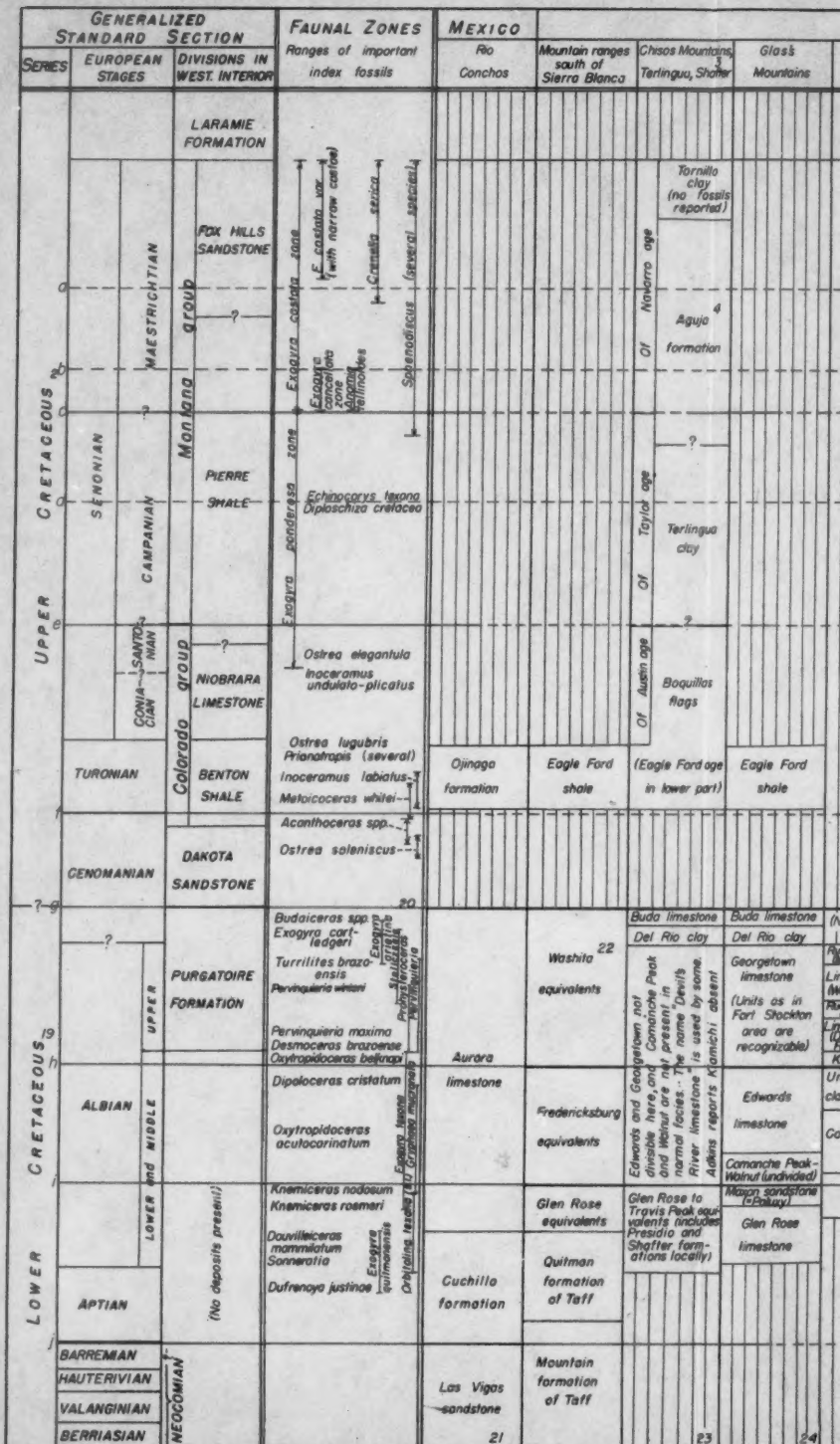
Red line *f*. Boundary between beds of Cenomanian and Turonian age.

Red line *g*. Boundary between the Comanche and Gulf series. This has usually been taken as the boundary between the Lower and Upper Cretaceous, but the Lower Cretaceous (Albian) age of the Del Rio clay, Buda limestone and Grayson marl member of the Denison formation, is disputed by some authorities.

Red line *h*. Boundary between the Fredericksburg and Washita groups.

Red line *i*. Boundary between the Trinity and Fredericksburg groups.

Red line *j*. Base of the Trinity group and beds of Trinity age.



1/ Numerals within the chart refer to the numbered annotations in the text

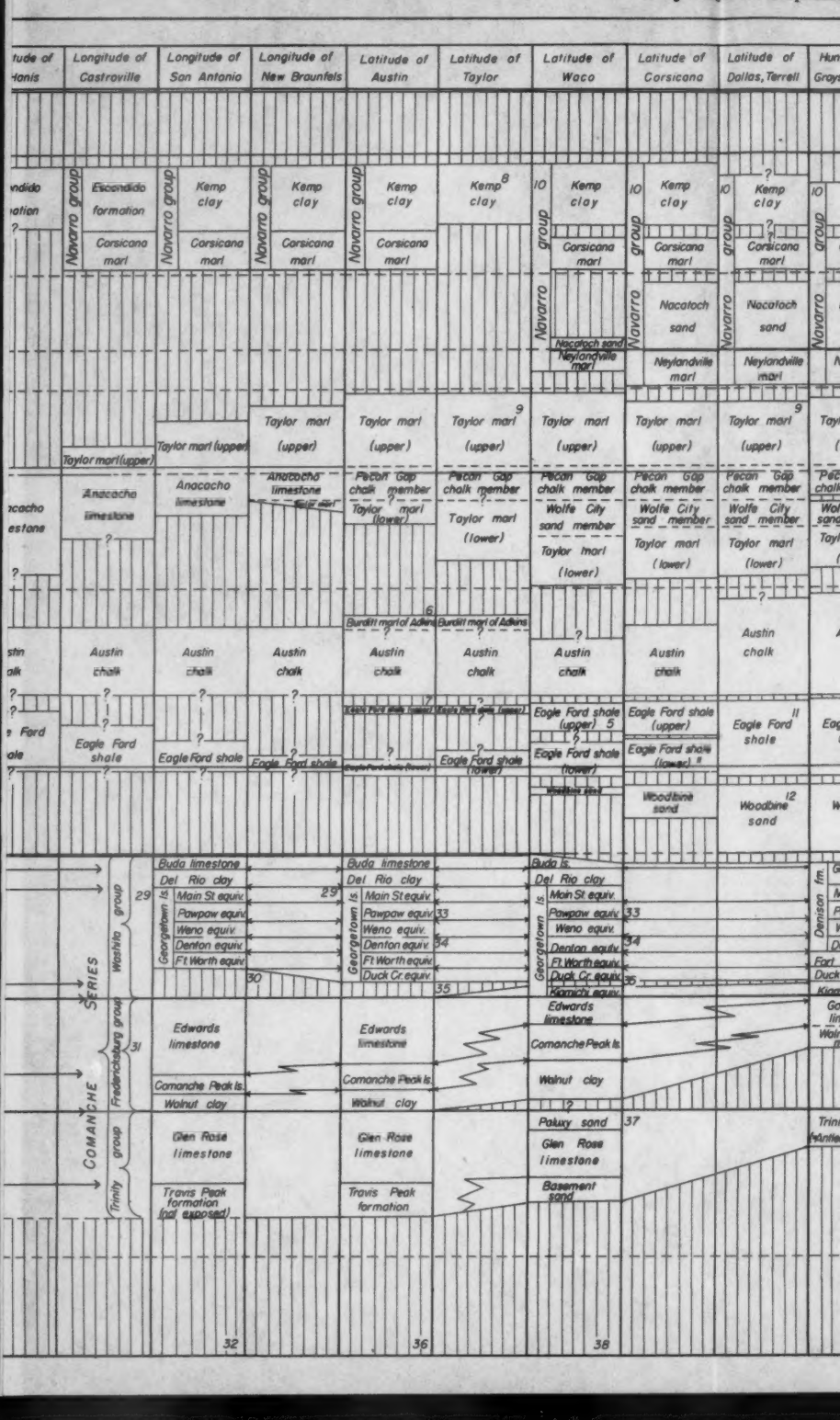
Chart No. 9 - CORRELATION O

TEXAS

Glass Mountains	Fort Stockton	Sierra Blanca	Diablo Plateau	Longitude of Eagle Pass	Longitude of Anacacho Mt.	Longitude of Uvalde	Longitude of D'Hanis	Longitude of Castroville	Longitude of San Antonio	Long New
				Navarro group	Escondido formation	Escondido formation	Escondido formation	Escondido formation	Kemp clay	Navarro group
								Corsicana marl	Corsicana marl	
					Olmos formation			Navarro group	Navarro group	
				GULF SERIES	San Miguel formation			Taylor marl (upper)	Taylor marl (upper)	Tay
					Anacacho limestone	Anacacho limestone	Anacacho limestone	Anacacho limestone	Anacacho limestone	
					Upson clay	Upson clay				
					Austin chalk	Austin chalk	Austin chalk	Austin chalk	Austin chalk	
Eagle Ford shale					Eagle Ford shale	Eagle Ford shale	Eagle Ford shale	Eagle Ford shale	Eagle Ford shale	Eag
uda limestone	(No higher beds exposed)	Buda limestone	(No higher beds exposed)	Buda limestone	Buda limestone	Buda limestone			Buda limestone	
el Rio clay		Del Rio clay		Del Rio clay	Del Rio clay	Del Rio clay			Del Rio clay	
eorgetown limestone	Rudistid ls. cap rock (Main Street age)	Georgetown limestone equivalent (with Kiamichi at base)	Marl and clay (Weno to Kiamichi age)	Devils River limestone as exposed at type locality	Devils River limestone	Devils River limestone			Georgetown ls. Main St equiv.	
Units as in Fort Stockton area are recognizable)	Limestone and clay (Weno-Pawpaw age)								Pawpaw equiv.	
	Rudistid ls. cap rock (Denton age)								Weno equiv.	
	Limestone and clay (Duck Creek and Fort Worth age)								Denton equiv.	
	Kiamichi clay		Sandstone						Ft Worth equiv.	
Edwards limestone	University Mesa clay of Adkins	Finlay limestone	Cox sandstone (replaces Finlay ls.)	Edwards limestone	Edwards limestone	Edwards limestone			Edwards limestone	
	Comanche Peak limestone			Comanche Peak ls.	Comanche Peak ls.	Comanche Peak limestone			Comanche Peak ls.	
omanche Peak - Walnut (undivided)				Walnut clay	Walnut clay				Walnut clay	
Kiowa sandstone (=Paluxy)	Basement sands	Cox sandstone		Glen Rose limestone	Glen Rose limestone	Glen Rose limestone			Glen Rose limestone	
Glen Rose limestone		Campagrande ls.				sand, clay, and gravel (Base concealed)			Travis Peak formation (not exposed)	
				Trinity group	Trinity group					
				Fredericksburg group	Fredericksburg group					
				Washita group	Washita group					
				COMANCHE SERIES	COMANCHE SERIES					
24	25	26	27	28					32	

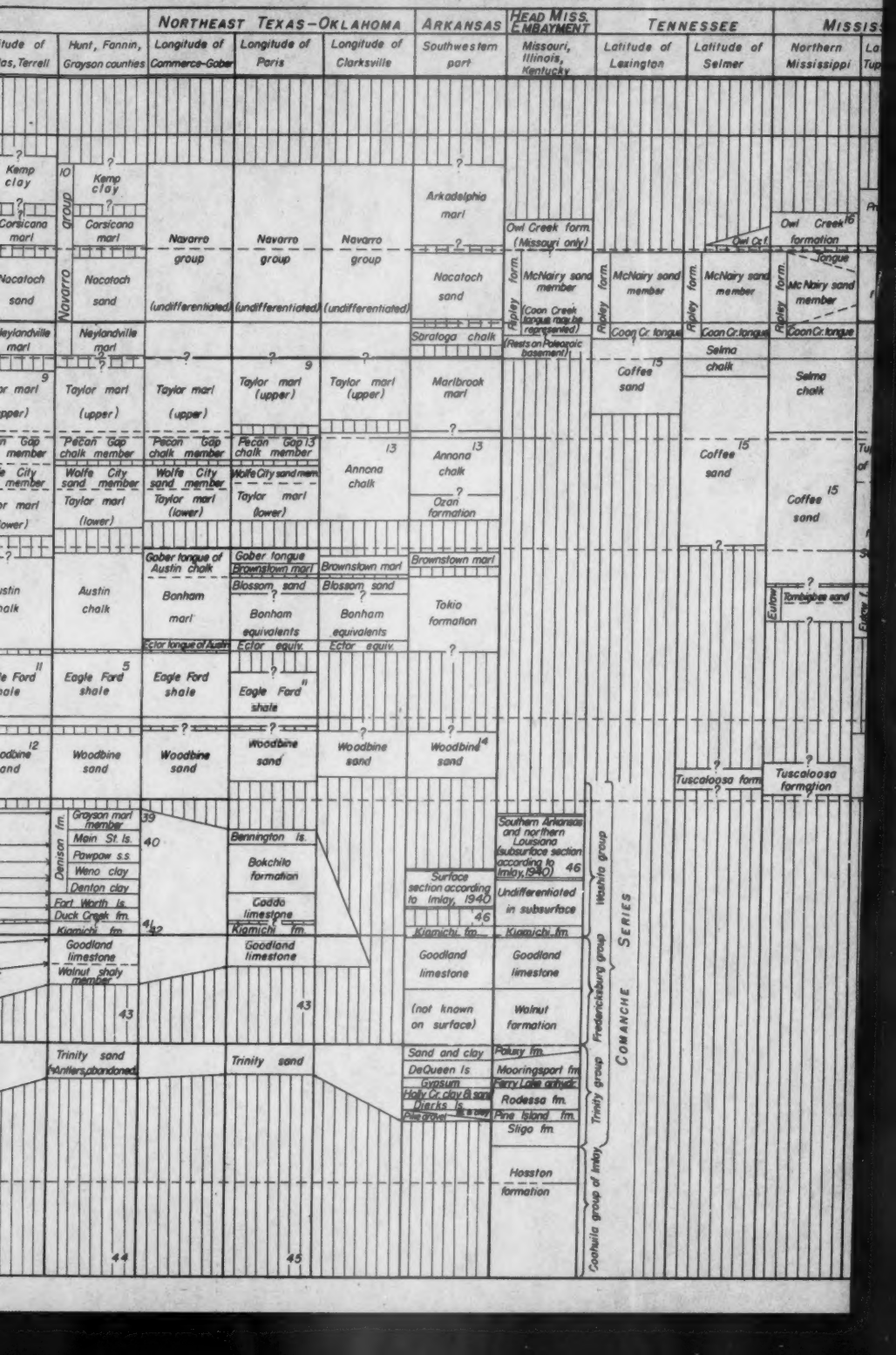
9 - CORRELATION OF THE OUTCROPPING CRETACEOUS FO

By Lloyd W. Stephens

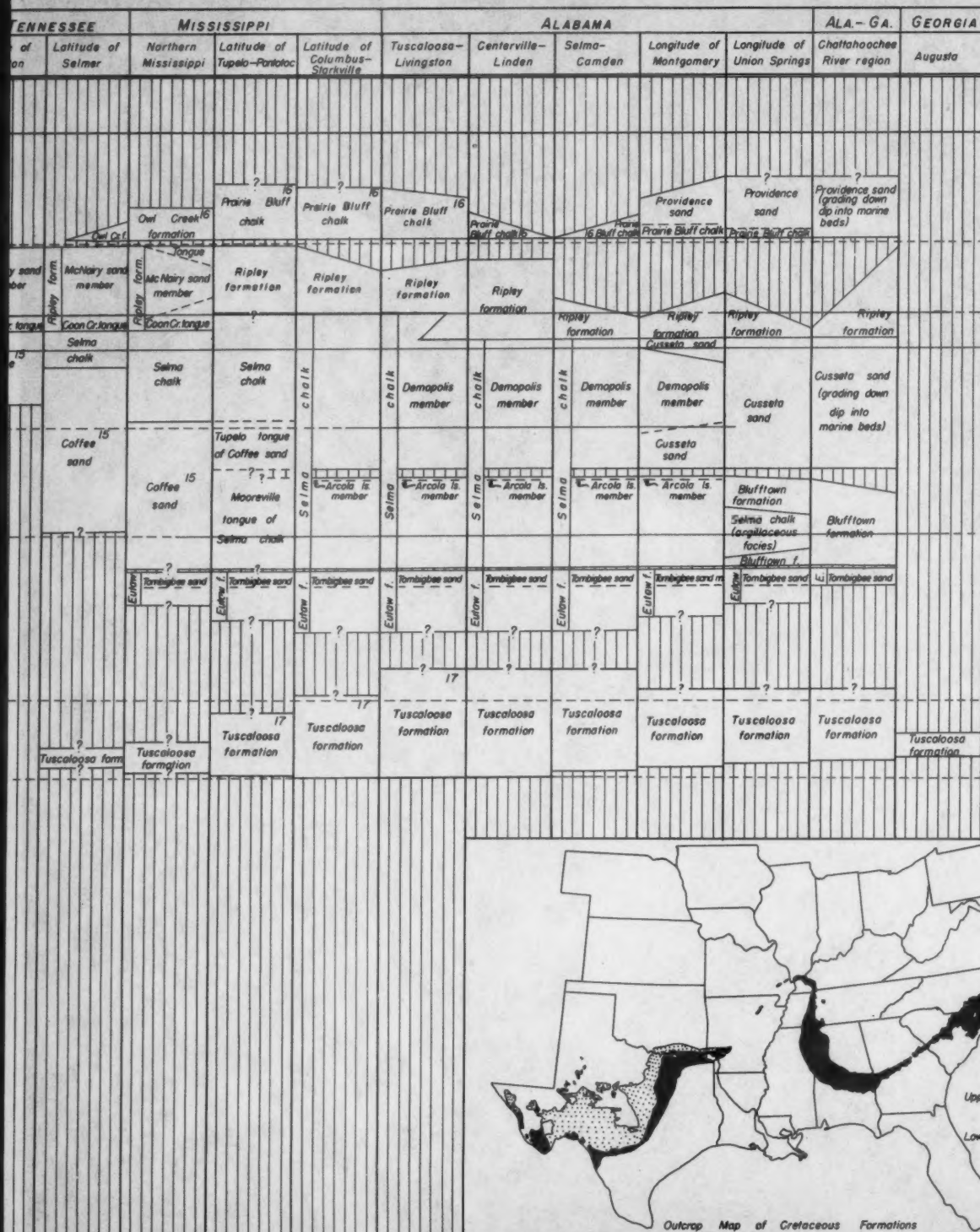


OUS FORMATIONS OF THE ATLANTIC AND GULF COASTAL PLAI

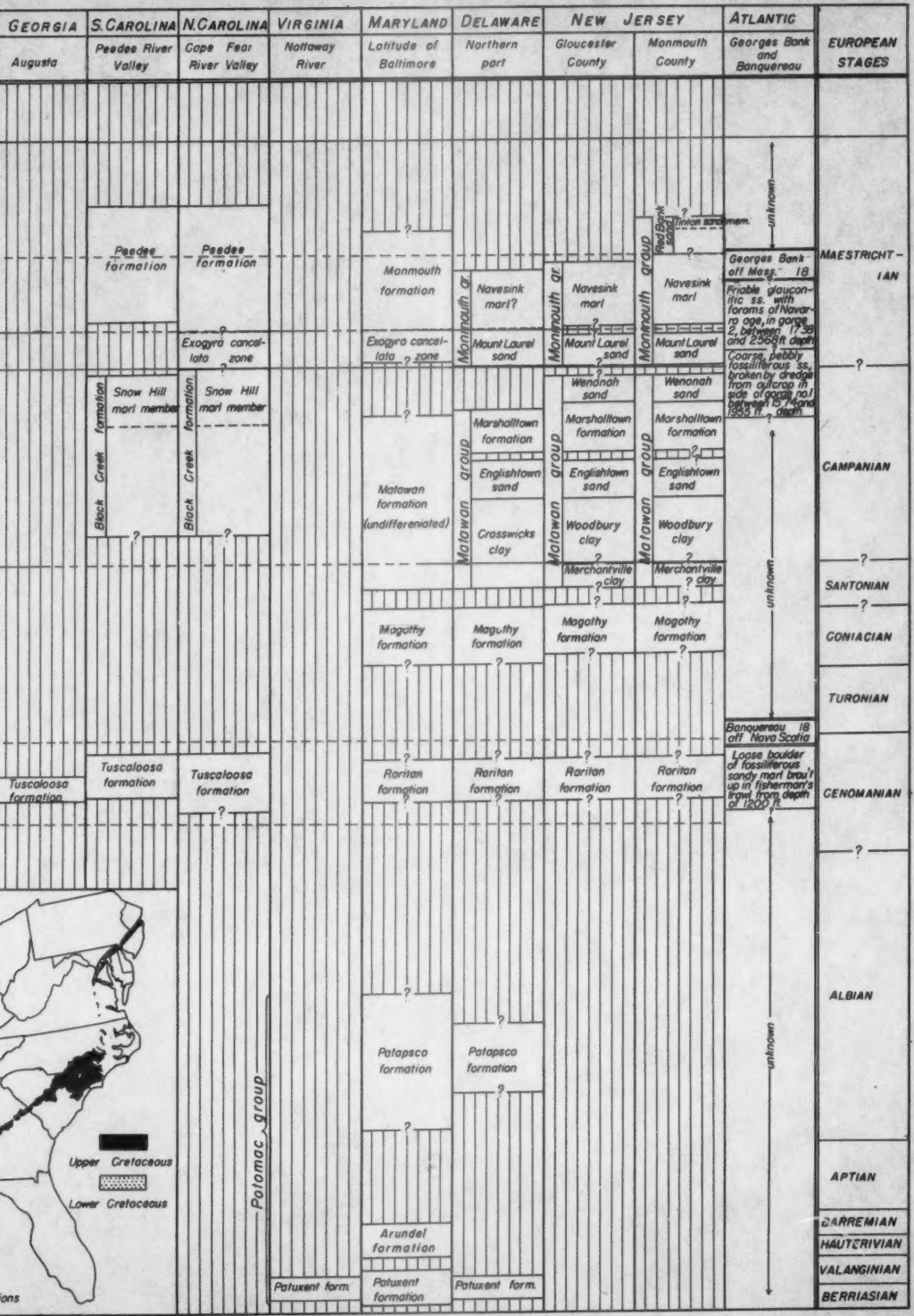
V. Stephenson, Philip B. King, Watson H. Monroe, and Ralph W. Imlay



F COASTAL PLAIN AND TRANS-PECOS TEXAS[1]



Prepared under the auspices of the Committee on Stratigraphy of the National Research Council, Carl O. Dunbar, *Chairman*.



BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
VOL. 53, PP. 449-512, 5 PLS., 3 FIGS. MARCH 1, 1942

ALKALINE AND CARBONATE INTRUSIVES NEAR BANCROFT, ONTARIO

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CONTENTS

	Page
Abstract	450
Geology	450
Introduction and acknowledgments	450
Alkaline intrusives in general	453
Limestones	455
Hastings Road section	456
Bancroft Complex	458
Carbonate rocks within the Bancroft Complex	462
General statement	462
Southern Carbonate Belt	462
Northern or Snow Road Carbonate Belt	463
Central or East Road Carbonate Belt	464
Fine structure	466
Nature of contacts	467
Question of scale	468
Petrography	469
Granite	469
Amphibolite and pyroxenite	470
Syenites and shonkinites	473
General statement	473
Potash-soda syenites and shonkinites	474
Albite syenites	483
Nepheline rocks	484
Late acid pegmatites and veins	487
Marble and intrusive carbonate rocks	488
Theoretical considerations	492
Origin of pyroxenite and amphibolite	492
Separate magma deficient in silica	493
Order of intrusion or solidification	494
General statement	494
Comparison with previous results	497
Origin of the alkaline rocks	499
Primary calcite and intrusive carbonate rocks	505
Comparisons with related areas	507
References cited	510

ILLUSTRATIONS

Figure		Page
1.	Index map of Haliburton-Bancroft field	454
2.	Urtite eye in foyaite, Snow Valley, Bancroft	487
3.	Time relations of major rock types	496

Plate — Facing page
1. Flowage of Grenville marble and carbonatite 456
2. Flow structures in carbonatite and shonkinite 457
3. Perthite and primary calcite in syenite 466
4. Syenite-mylonite and lime mylonite 467
5. Geologic map of Bancroft area 512

ABSTRACT

The alkaline intrusives of the Bancroft area lie along the contact between the "Laurentian" granites and the Grenville marble. Alkaline rocks pass in sweeping arcs about two predominantly granitic areas. The principal alkaline intrusives fall into two quite distinct groups: a series of saturated or nearly saturated rocks ranging from syenite through shonkinite to perknite; an undersaturated group including urtite, ijolite, foyaite, and jacupirangite. Three sill-like bands of marble lie within the alkaline complex but are in the main indistinguishable from the Grenville marble immediately south of the complex.

The oval-shaped granite areas are often heavily contaminated with bands and lenses of amphibolite. About these amphibolite impurities the granite develops a marginal syenitic facies, and most of the shonkinites have been formed by the intimate mixing of amphibolite and syenitic liquid. The nepheline rocks show no constant association with syenite, granite, or amphibolite. Typically the coarse urtite or nepheline pegamatite lies within limestone. There seems to have been only a small supply of truly foyaitic magma, and most of the undersaturated rocks are migmatites or hybrids. Where urtite has been injected into amphibolite, ijolites and jacupirangites have been formed; where it penetrates syenite, foyaite results.

The alkaline rocks as a whole are younger than the granites of the area but are themselves cut by acid pegmatites. Some of these late pegmatites are albite-aegirine-quartz rocks closely related to the alkaline suite.

The carbonate rocks of the alkaline complex are intrusive in the sense that they cut and enclose most of the other rocks of the complex, but their intrusive habit is merely the final expression of a long metamorphic history. The region is rich both in primary calcite and in intrusive carbonate rocks, but the primary calcite is not intrusive, and the intrusive carbonate rocks are not primary.

The granite-syenite-amphibolite association is best explained by the limestone-syntexis hypothesis, and nothing in the field relations of the carbonate-urtite group contradicts the theory. None of the carbonate is truly magmatic, a small percentage of it is hydrothermal, but the vast bulk—including that which forms carbonate-intrusives—is surely metamorphic.

GEOLOGY

INTRODUCTION AND ACKNOWLEDGMENTS

The field association of feldspathoidal intrusives with metamorphosed limestone, since proved very common, was first given prominence in 1910 through the outstanding work of Adams and Barlow (1910) in the Haliburton-Bancroft area of Ontario. Their description of this region brought into sharp relief a puzzle which was really a synthesis of two previously independent questions.

The first of these two questions concerned the origin of nepheline-bearing rocks. Adams and Barlow showed that every occurrence of these rocks in the area described by them lies either between granite and limestone, between granite and amphibolite formed from limestone, or within limestone or amphibolite close to the margin of the associated

granite. They concluded that the magma which had given rise to the granite of the area was responsible also for the silication and metamorphism of limestone and they considered the nepheline rocks closely related to the granites. Concerning the exact nature of this relationship they said little, although they described an apparent transition of granite into foyaite at Tory Hill. The notion that magma poor in silica might be generated as a by-product of reaction between granitic magma and limestone almost suggests itself from their work but is nowhere explicitly stated by them.

The treatise of Adams and Barlow was followed almost immediately by a paper of Daly (1910) containing the first formal statement of what he chose to call the "limestone-syntexis" hypothesis of the origin of feldspathoidal rocks. Daly maintained that the silication of marble necessarily implies a proportionate decrease of silica in the reacting magma and that feldspathoidal rocks are the solid equivalents of such desilicated magmatic fluids. Daly's first paper was in the main a summary of all known occurrences of feldspathoidal rocks and it consequently gave no special prominence to the Haliburton-Bancroft region. Nevertheless, it is more than likely that the Haliburton-Bancroft field exerted a powerful influence—perhaps even the most powerful single influence—upon the development of the limestone-syntexis hypothesis. The importance Daly attached to the field soon became clear when he wrote (1914) that "the Haliburton-Bancroft region in Ontario offers most striking evidence favoring sedimentary control in the formation of nephelite syenites." Later (1918) he was even more emphatic, discussing at length Foye's then recently published study of the syenites and pegmatites near Gooderham.

Daly's hypothesis was readily accepted by some petrologists and as firmly rejected by others. During the past 30 years geological journals have devoted much space to discussion of the problem. Among petrologists who have given partial or full support to the idea of limestone-syntexis are Allen, Barth, Brögger, Brouwer, Högbom, Kranck, Shand, and Stansfield. Chief among its opponents have been Bowen, Harker, Holmes, Smyth, and Tilley.

The Haliburton-Bancroft field may almost be called the type-field of limestone syntexis and yet it has been the subject of very little of the detailed study necessary as a check on the theory. The nepheline pegmatites in the western portion of the field were described by Foye (1915). Analogous rocks near the eastern limits of the area were briefly described by Osborne (1930). Keith (1939) has recently described a large but atypical foyaite mass near Lakefield, in the southwest.

In the field which more than any other may be said to have given

life to it, the status of the limestone-syntexis hypothesis is indeterminate. Foye felt that the evidence supplied by his investigation provided strong support for Daly's hypothesis. Osborne is perhaps more negative than not but remains on the whole non-committal. Keith rejects *in toto* the limestone-syntexis hypothesis.

The pendulum of opinion has thus swung through a full half-period, while the facts of the matter still await adequate presentation. It seems presumptuous to suggest that evidence gathered by five competent geologists working in the same area is incomplete, but no other conclusion is permissible when the same rocks are used by two men to develop and support a given theory, by a third to suggest the inapplicability of the theory, and by a fourth to reject the theory.

The second and equally important problem of the Haliburton-Bancroft field is the many-sided question of limestone metamorphism. The stratigraphic identity of the comparatively unmetamorphosed Grenville limestone of the south with the coarse marble, marmorite, amphibolite, and pyroxenite of the north was clearly established by Adams and Barlow. In other areas, however,—Fen, Alnö, and Magnet Cove, for instance—the sedimentary origin of the highly metamorphosed limestones associated with alkaline intrusives is far from obvious. To account for the intrusive character of the Fen marble, Brögger suggested the injection of a separate carbonate magma formed by the pure melting of limestone. For the same rocks Bowen later suggested a hydrothermal origin. The concept of a true carbonate magma has recently been revived by Von Eckermann, Tomkeieff, Dixey, and Campbell Smith.

Flowage of marble is possibly nowhere better displayed than in the Haliburton-Bancroft field. It was well described by Adams and Barlow, but their account was necessarily somewhat generalized, and they provided no information concerning the connection between marble flowage and the emplacement of alkaline rocks. New information concerning the metamorphism of the Grenville limestone has been accumulated in the course of this investigation. The relations between the silication, flowage, and intrusion of marble and the emplacement of alkaline rocks have been carefully studied.

Whatever the final verdict concerning limestone syntexis in the Haliburton-Bancroft field, the geology of the alkaline rocks is so closely involved with that of the Grenville marble and limestone that the two cannot be studied separately. The aim of this paper is to provide a much-needed factual basis for, and at least a partial resolution of, the two-fold problem of limestone metamorphism and alkaline intrusion, in a region whose importance with regard to the study of these phenomena can hardly be overestimated.

Before offering the results of his own investigation the author wishes first to express his admiration for the work accomplished by Adams and Barlow in a little-known and rather poorly exposed region of great geological complexity. No major conclusion reached by these pioneers failed to stand the test of detailed examination, and the writer's indebtedness to them is shared by all who have worked or will work in the area. To those familiar with the problem his obligation to Professor R. A. Daly will be obvious, inasmuch as it was Professor Daly who first grasped the full significance of the granite-foyaite-limestone association.

The author's first visit to the Haliburton-Bancroft area was made under the supervision of Professor G. M. Kay. The problem was suggested by Professor S. J. Shand, and it would be impossible for the author to express adequately either his indebtedness or his gratitude to Dr. Shand, without whose patient guidance and penetrating criticism this paper could not have been written.

ALKALINE INTRUSIVES IN GENERAL

The Haliburton-Bancroft region occupies about 4000 square miles in Hastings, Haliburton, Renfrew, and Nipissing counties, central Ontario. On the basis of outcrop areas, the map sheets prepared by Adams and Barlow (1910) show a rough gradation from granite in the northwest through a zone of increasing contamination with marble, to marble terrane in the southeast.

The southeastern portion of the Haliburton-Bancroft area consists of Grenville marble and amphibolites, together with small amounts of gabbro and rhyolite. The northern section is composed of a varied assortment of shield granites, predominantly gneissic and often contaminated with amphibolite lenses and streaks. From Craigmont (*see* Figure 1) in the northeastern corner of the map sheet, a band of mixed rocks many miles wide stretches diagonally across the field, finally passing under Paleozoic beds at Stony Lake along the southwestern boundary. In the northern portion of this mixed rock zone marble and amphibolite occur as narrow streaks and bands largely or entirely enclosed in granite. To the south the situation is reversed, and isolated streaks, knobs, and lenses of granite form islands in the limestone amphibolite terrane. In contrast to the dense, medium-grained, blue-black Grenville limestone of the southeast, the marble of the contact zone is usually coarse, white or gray, and strongly silicated.

The alkaline intrusives are found only in this broad contact zone. Excepting the recently described occurrence at Blue Mountain, Methuen Township (Keith, 1939), they are all well to the north, where the dominant country rock is granite. Their maximum development is reached

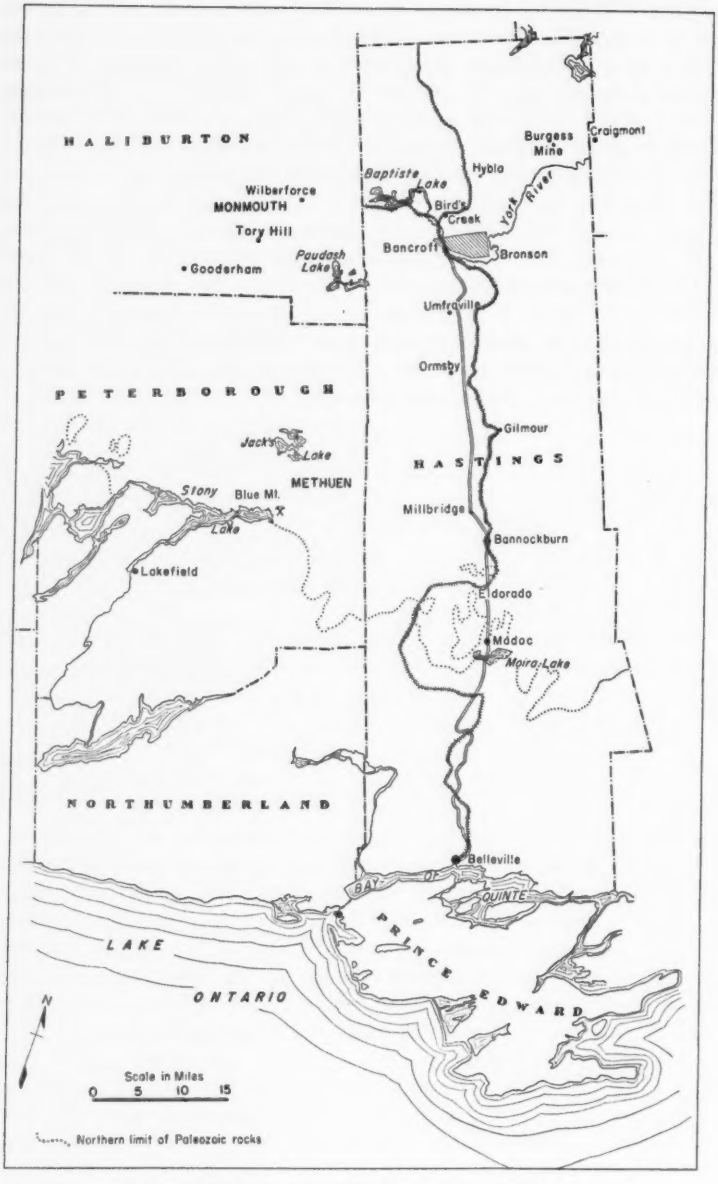


FIGURE 1.—*Index map of Haliburton-Bancroft Field*

in the eastern portion of the field, where they form a narrow belt between the northern "batholithic" granites and the predominantly granitic region of the mixed rock zone. Numerous but scattered outcrops have been traced from Craigmont 20 miles southwestward into Dungannon township, where the alkaline belt broadens suddenly and swings to the west. From Bronson westward it thins gradually and either pinches out or is lost beneath cover about 2 miles west of Bancroft. Nepheline rocks again outcrop about 5 miles west of Bancroft, and a narrow band has been mapped by Adams and Barlow south of Diamond Lake, where the intrusives parallel closely the granite-marble contact from which they are separated by a narrow seam of marble. Farther west the nepheline rocks lose contact with the granite terrane and are found in the northern mixed rock zone, where they lie near or in contact with granite patches which are themselves isolated from the main mass by tongues of marble.

The predominantly gneissic and pegmatitic alkaline rocks have been intruded into the crust along the margin of the shield granites and the Grenville terrane. At Gooderham and Egan Chute numerous small bodies of coarse nepheline pegmatite and migmatite are without visible or easily inferred granite contact. At Blue Mountain no marble foyaite contact is exposed. All other sizable bodies of foyaite or syenite are intercalated between granite and limestone, the larger masses of syenite frequently forming border facies between granite and marble or foyaite, the foyaite commonly separated from granite and syenite by a thin, discontinuous veneer of marble. As Adams and Barlow (1910) pointed out, it is often possible to trace a sequence from granite through syenite into foyaite and ultimately into limestone. Even where large quantities of marble are not exposed, as at Blue Mountain, Methuen Township, the foyaite is separated from granite by syenite. The Tory Hill complex, described in some detail by Adams and Barlow, is an unusually good example of the complete granite-syenite-foyaite-marble sequence. The word "sequence" is used here in preference to "transition" for reasons which will be apparent later.

This zonal arrangement of the alkaline rocks is of great potential importance in any discussion of the limestone-syntexis hypothesis, but field relations are so confused that no proper evaluation can be made without considerable further description.

LIMESTONES

In the Haliburton-Bancroft field the Grenville series—elsewhere heterogeneous in the extreme—is represented by one of the most remarkable known developments of limestone and limestone derivatives. It

may be coarse or fine; white, blue, pink, gray, or black; finely laminated or coarsely banded; but it is in most cases a carbonate rock or a calcite-bearing amphibolite. Many of the amphibolites can be traced into relatively unsilicated marble, and this relationship is even more easily demonstrated in the less common pyroxenites. The characteristic heterogeneity of the Grenville is not entirely lacking. Conglomerate, quartzites, cherts, slaty, and tufflike beds are all known, and some of the paragneiss of the district may be Grenville. Such variations are distinctly rare, however, and the only prominent non-calcareous member is a dense black quartzite which is ubiquitous rather than abundant.

Most of the southern portion of the field, particularly the southeast, is underlain by Grenville limestone or its derivatives. These become less and less common toward the north and northwest until in the northern granite terrane relatively unaltered "limestone" is virtually unknown, and amphibolite, pyroxenite, and coarse marble are found only as scattered lenses in the country gneiss. The Haliburton-Bancroft field thus forms a limestone-contact zone of extraordinary size.

The quantity of limestone, marble, and related amphibolite cannot be accurately estimated. Even the "relatively unmetamorphosed limestone" is thoroughly recrystallized and isoclinally folded except in the southern fringe of the area. In the western part of the field Adams and Barlow (1910, p. 31) estimate the thickness of the limestone to be a little over 9000 feet. For the eastern or Bancroft region they estimate 94,000 feet, of which 50,000 feet is pure limestone and the remainder chiefly closely related amphibolites. These thicknesses are measured laterally on steeply dipping beds, and there is no way of guessing what the original thickness may have been.

Some explanation of the extraordinary thickness of the Grenville is required. It has been suggested that great thicknesses of this sort are only apparent, that they have been produced by a surface crumpling rather than an intensive and extensive folding. This would imply that the present Grenville is a relatively shallow veneer on the more or less undeformed floor of the basin in which it was deposited. Arguments to be developed later in connection with the mode of intrusion of the alkaline rocks lend little support to the view that the deformation of the Grenville series is merely a surface crumpling. The present thickness of the carbonate rocks is measurable in tens of thousands of feet, and there is no direct field evidence that the original thickness was of a different order of magnitude.

Hastings Road section.—The Grenville section exposed along the Hastings Road was mentioned but not described by Adams and Barlow

FIGURE 1. BANDED BLUE AND GRAY LIMESTONE, MILLBRIDGE

FIGURE 2. COARSE WHITE MARBLE CUTTING AND ENCLOSING FINE-GRAINED QUARTZITE AND BLACK LIMESTONE
North of Gilmour, Hastings Road.

FIGURE 3. COARSE WHITE CARBONATITE
Bancroft (Pl. 5, Point A). Note flow line in marble passing about U-shaped granite enclosure.

FIGURE 4. LIME MYLONITE
Clear Lake Road near intersection with East Road (Pl. 5, Point C).

FLOWAGE OF GRENVILLE MARBLE
AND CARBONATITE

FIGURE 1. COARSE WHITE CARBONATITE
With U-shaped enclosures of granite, Bancroft (Pl. 5, Point A).

FIGURE 2. POWDERY-SYENITE BOULDER
Enclosed in biotite shonkinite, Bancroft (Pl. 5, Point A).

FIGURE 3. LENS OF ALBITITE
Enclosed in shonkinite-gneiss, Bancroft (Pl. 5, Point B).

FLOW STRUCTURES IN CARBONATITE AND SHONKINITE

(1910). The Grenville beds in the southeastern portion of the field strike east-west, with a vertical or steep southerly dip. For upwards of 30 miles, from the village of Millbridge northward, the Hastings Road runs almost perpendicular to the strike. Most of the region is devoid of outcrop, but the soil mantle is excessively thin throughout. Grading of the recently rebuilt highway has produced rock-cuts through almost every high-spot, and from Millbridge to Bancroft one is rarely out of sight of fresh exposures. On either side of the road the bush closes in rapidly.

The first good exposures of the southern Grenville beds are found along the side road connecting the village of Millbridge and the railroad siding. The relatively unmetamorphosed Grenville here consists of thin, fine-grained, interbedded blue and gray limestone (Pl. 1, fig. 1). The gray facies is invariably more closely crumpled than the blue and in a few places it seems to have flowed through and about the latter. Coarse white calcite seams parallel or transect both facies, but the formation of these coarse white streaks has not in any way affected trains and laminae of non-calcareous impurities in the limestone.

To the north along the Hastings Road, the coarse white calcite becomes increasingly important. At first it forms only scattered, randomly oriented, and discontinuous streaks and seams. These become more and more prominent, comprising in extreme cases as much as 20% or 30% of a given outcrop. Finally, the first broad bands of marble appear. These are usually intercalated parallel to the main "bedding" or parting planes of the fine-grained limestone; in general the larger a single streak or band of coarse calcite the less sharply it transects the structure of the limestones.

In favorable outcrops the slender, cross-cutting seams may be seen to take their origin from these broad conformable bands much like the pegmatitic and aplitic apophyses of granites. There are occasional sill-like bands of breccia in which angular or rounded fragments of black chert or dense, fine-grained blue-black limestone are held in a matrix of coarse white marble. The road-cut just north of Gilmour exposes a broad breccia band, and many others may be seen between Gilmour and Bancroft.

The blue and gray limestones become less important to the north and are finally found only as scattered bands in the now-dominant coarse white member. The Grenville section is interrupted by a narrow tongue of the Tudor gabbro, but the limestone-marble complex north of the gabbro is much like that to the south.

In a remarkable outcrop formed by a road-cut about 10 miles south of Bancroft, coarse white marble clearly cuts and encloses dense black

cherts and limestones (Pl. 1, fig. 2). Regardless of their origin or source or even of the specific mode of emplacement, the broad, usually concordant marble bands are here undoubtedly intrusive into the less metamorphosed members of the Grenville series. If the coarse marble were granitic in composition no one would hesitate to call it igneous. If, on the other hand, the intruded and included rocks were igneous—particularly alkaline—many would consider the coarse calcite rock itself igneous.

Immediately south of Bancroft, road cuts are almost entirely in coarse marble. The fine-grained facies and its accompanying dark chert are rarely absent, however, and elsewhere in the area they have been found occasionally within the northern granite terrane. The Hastings Road section ends abruptly under thick cover a little over a mile south of Bancroft. The last outcrop contains the usual coarse white marble with minor amounts of chert and dark limestone.

The road passes through a gap in the great amphibolite ridge which forms the southern boundary of the Bancroft alkaline complex. Grenville marble is nowhere exposed in contact with this amphibolite, but the two are often close neighbors. The broad swamp south of the East Road is underlain by marble and amphibolite; exposures in the actual floor are usually limestone, while the small knolls and ridges which rise above the swamp level are commonly amphibolite. Marble is frequently separated from amphibolite by only a few yards of swamp grass or ooze. Sometimes the contact can be placed within a few feet along the flank of a ridge.

BANCROFT COMPLEX

The geology of the Bancroft complex might almost be inferred from the general description already given. Located in the east-central portion of the field, it is bounded on the north by the granite terrane and on the south by marble and amphibolite of the mixed-rock zone.

The area in which alkaline rocks are exposed is roughly triangular, its apex lying along the Monck Road, a little west of Bancroft. The York River, flowing southeast as it leaves Bancroft and cutting abruptly to the north at its intersection with the East Road, outlines fairly well the hypotenuse and base of this exposure area. The altitude of the triangle would be given by an extension of the Snow Valley Road, in northern Bancroft, through Clear Lake and thence due east about 2 miles, almost to the York River. The area thus enclosed is about 15 square miles. Its eastern quarter is heavily drift covered and does not appear on the accompanying map (Pl. 5). At least a third of this area shown in Plate 5 is under cover. Another third is underlain by various

granites of the basement complex, some of which are related to the alkaline intrusives. The remainder consists of about equal quantities of foyaite, syenite-shonkinite, and carbonate-rock.

Variation of rock type either along or across the strike is rapid and oscillatory. For instance, the foyaite exposed in the railroad-cut south of Bancroft station disappears under the valley of the York River and is succeeded to the east along the trend of the outcrop (which is also the strike of the foliation) by coarse marble which soon gives way to an intricate series of shonkinites and syenites. These are in turn displaced by quartz syenite. The entire series of transformations is effected in less than a mile. Variations across the strike are on a much finer scale. The "foyaite" of the railroad cut carries several foot-broad bands of marble. The "granite" of the Copper Lake area is a complicated tangle of granite, syenite, shonkinite, scapolite-gneiss, and amphibolite in which granite of one type or another forms most of the outcrops.

Small-scale deflections and inversions of foliation—or lineation—direction are the rule rather than the exception; but in a general way outcrop-trend and foliation-strike are parallel in the alkaline rocks. Scarcity of outcrops and low content of dark minerals make impossible any generalizations concerning the fabric of the granites. Where they are exposed near or in contact with the alkaline intrusives, however, they are usually appreciably richer in dark minerals, and in such cases the foliation or lineation of the granite parallels that of the younger intrusives.

As a result of the bewilderingly rapid mineralogical variation and the absence of any well-defined large-scale structure, an accurate map on any convenient scale is not possible. The symbols on Plate 5 represent only the rocks which are most prominently exposed in the areas they cover. Subordinate types are almost always present in any given area, and their concentration is frequently great enough to require schematic representation on the map.

The nature of the rocks and the insufficient evidence preclude an adequate discussion of structure. No single large-scale structure became apparent as the result of the writer's field work. The alkaline rocks pass in curving bands about two dominantly granitic, oval-shaped areas immediately south of the main granite terrane. The northern granite is best exposed through the entire length of the high ridge (the Eagle's Nest) which forms the northern flank of the Snow Road Valley and closely resembles the "red-gneiss" of Adams and Barlow. It is almost devoid of dark minerals over large stretches, and there are none of the prominent amphibolite lenses and bands so common in the granites of the alkaline complex immediately to the south.

Of the oval-shaped granitic masses more or less isolated from the northern granites, the western (Copper Lake) area is heavily contaminated with amphibolite and lenticular or sill-like bands of syenite, shonkinite, and scapolite-gneiss, while the larger (Bronson) mass is comparatively homogeneous. In the center of this latter area amphibolite lenses are infrequent, and neither syenite nor shonkinite has been found. Toward its margins the granite becomes increasingly impure, and lenses and streaks of amphibolite become the rule rather than the exception. On the east, west, and south, this marginal granite-amphibolite hybrid passes by a series of abrupt transitions into syenite and shonkinite, and these are succeeded by or interbanded with foyaite and marble.

The relation of these granitic areas to the northern "batholithic" granites is not clear. Tongues of the alkalic and carbonate intrusives stretch inward along the contact from both sides of the Copper Lake area, and a broad wedge of shonkinite and foyaite (continuous with that of the Princess Quarry) intervenes between the northern granites and the northwestern limit of the Bronson granitic area; but this wedge is soon lost under dense cover. The combination of poor outcrops and large quantities of late acid pegmatite also obscures the relationship between the Copper Lake granitic area and the northern granite terrane.

At the present erosion level the Bronson granite seems to form a peninsula in the alkali-carbonate-intrusives, while the Copper Lake granite area is either truly insular or has at most a slender, dike-like connection with the northern granite "mainland." Nothing in the field data suggests that these relationships persist in depth.

The rocks which isolate these granitic islands or peninsulas fall into three broad categories—syenite-shonkinite,[1] nepheline rocks, and carbonatite.[1] The syenite-shonkinite series is concentrated in or along the amphibolite rich zone of the granite. There is no gradual transition from granite to syenite, but the syenite sporadically carries a variable percentage of quartz. Syenite and quartz syenite differ from certain facies of the granite only in quartz content. Thus, although there is no simple gradation, there is at least a persistent geological association and a mineralogical transition between the two. A somewhat similar relationship exists between the amphibolite inclusions in the granite and the amphibolite-shonkinites, with feldspar increasing gradually from zero in amphibolite to upward of 60% in shonkinite, and much more in syenite.

[1] In this paper the term shonkinite is used to include all saturated alkali-feldspar or albite rocks with color index greater than 30. Carbonatite means simply intrusive carbonate rock. The term "intrusive" is in this case purely descriptive and carries no implication of magmatic origin. Unless otherwise noted, rock names used in this paper follow the usage of Shand (1921, 1927).

Between foyaite and syenite there is no such relationship. The potash-soda feldspars which characterize most of the syenite group are never important and are often negligible in the foyaites, in which albite is the dominant feldspar. Biotite is the common dark mineral of the foyaites. Except in the very coarse facies, hornblende is the common dark mineral of the syenites and shonkinites. The proportion of quartz falls irregularly but without sharp break from normal granite to quartz-free syenite. But foyaites poor in nepheline are rare. Many syenite slides were stained for nepheline, and where there was doubt about the presence of the mineral it was usually absent. In the few specimens which contain minor amounts of nepheline, it is usually thoroughly decomposed and represented by fibrous or micaceous pseudomorphs. Except in hornblendic migmatites the color index of the nepheline rocks rarely rises above 20. It is for the most part well below 15.

The association of carbonatite with foyaite has been mentioned. The Copper Lake granite area is bounded on the south, east, northeast, and northwest by marble and foyaite. The Bronson granite and the southern syenite-shonkinite band are cut off on the east by a complexly folded body of marble carrying huge inclusions of granite. These "carbonatites" are rarely less than 85% carbonate. Like the carbonatites of Fen, Alnö, and Chilwa, those of the Haliburton-Bancroft area are of intrusive habit. All members of the intrusive complex except the nepheline-bearing suite have been found as boulders or angular fragments included in the flow-marble. In the shonkinites there is evidence for the replacement of feldspar by calcite as suggested by Bowen (1924) at Fen, but these rocks are rarely more than 20% carbonate. In the carbonatite proper only a negligible fraction of the carbonate has been introduced as a post-consolidation replacement of silicates. As shown in the theoretical discussion, the conditions are such as to render equally untenable the hypothesis of a liquid carbonate-magma. In the Haliburton-Bancroft field there can be no question of the metamorphic and initially sedimentary origin of the vast bulk of carbonate. The term "carbonatite" is used here only because of its previous use in related areas.

Coarse acid pegmatites have been intruded along the syenite-carbonatite contact on the north and south borders of the Copper Lake granite, and similar pegmatites are found in smaller bodies throughout the field. Quartz, "hastingsite," and aegirine veins cut all other rocks including carbonatite.

A narrow but apparently continuous band of amphibolite bounds the alkaline complex on the south, forming a steep ridge overlooking the swampy valley of the York River. A few outcrops of marble have been found between it and the river, but almost all of this territory is under

thick cover. The region south of the York River has been mapped by Adams and Barlow as Grenville marble. Outcrops are poor, and on a scale such as that of Plate 5 most of this area would have to be marked as drift-covered. All observed outcrops for at least 3 miles to the south are either Grenville marble or its derivatives.

CARBONATE ROCKS WITHIN THE BANCROFT COMPLEX

General statement.—Within the alkaline complex there are three principal east—west-trending belts of carbonate rock, the southern member forming a thin but persistent septum between the alkaline intrusives and the amphibolite ridge, the central band cutting through the center of the complex along the East Road, and the slender northern tongue extending for a short distance along the contact of the alkaline rocks and the northern granite.

These belts converge toward the west, markedly enough to suggest an actual juncture. The intersection of the southern and central bands would fall in the vicinity of the Bridge Street dam of the York River, Bancroft, and the northern spur would intersect the main marble band formed by this juncture considerably farther to the northwest, about at the western limit of the Bancroft complex. Marble does outcrop at the suggested intersection of the southern and central bands, forming one of the islands on which the dam is anchored. It is not clear whether this outcrop marks the actual junction or is an enlargement of one of the carbonate folia intercalated in the foyaites exposed in the railroad cutting immediately to the west. The suggested intersection of the northern marble spur with the main marble body is drift-covered, and the nearest outcrops are red granite. Possibly this northern spur swings gently southward and is represented west of the York River by the marble which forms the floor of the meadow opposite the Roman Catholic Church in the village of Bancroft. The suggested joinings are possible and even probable, but neither is susceptible of proof. The surface convergence raises but cannot answer the question of the possible continuity of the various marble belts in depth. Any broad interpretation of the structure of the area hinges on this point, and for this reason none is attempted.

Southern Carbonate Belt.—A narrow belt of coarse white marble intervenes between the amphibolite ridge and the bulk of the alkaline intrusives for almost the entire length of the complex. On the west it forms the floor of the dense swamp southeast of the town of Bancroft. To the east, due south of Bronson, it is well exposed on the Hawkins properties (Pl. 5, point G), and large quantities of coarse white marble on the Goodkey farm (Pl. 5, point H) may be an extension of this belt. The poorly exposed western portion of the band is sill-like, while the

bulging eastern termination on the Goodkey farm apparently cuts across the strike of granite and syenite, is closely folded, and carries large blocks of granite.

The marble of the southern band is identical with the Grenville exposed immediately south of the amphibolite ridge, and there is no reason to suppose that its history has been significantly different. Contacts of marble with the main mass of amphibolite have not been found. In the swamps southeast of Bancroft the two are frequently exposed within a few feet of each other, and any transition must be very abrupt. Coarse white marble exposed in the road cut just east of the York River crossing of the East Road carries elongate enclosures of an amphibolite indistinguishable from much of that which forms the bounding southern ridge.

Northern or Snow Road Carbonate Belt.—The northern carbonate belt is known only from a few scattered exposures along the crest of the small ridge just south of the "Eagle's Nest." Coarse, foliated phlogopite-marble is well exposed at the western end of this ridge. Farther west the entire complex is obscured by the thick drift of the York River Valley. Eastward the ridge crest is under cover, but an occasional streak of marble and a few pyroxenite lenses penetrate the thin soil mantle. Farther east these soon give way to a coarse acid pegmatite.

The marble strikes east-west, dips steeply south, and seems to be underlain by red granite-gneiss. Stratigraphically above it, the center of the valley is occupied by foyaite, while the southern flank consists of syenite, amphibolite, and various scapolite gneisses. Thus the northern carbonate belt, like its southern counterpart, forms a thin shield between country rock and alkaline complex proper.

Pyroxenite occurs in this northern carbonate belt, both as boulders scattered along the line of strike and, in a few instances, in lenses apparently *in situ*. These pyroxenites vary greatly in grain size but are of fairly constant mineralogy, consisting almost entirely of acmite-diopside with a few per cent each of fresh honey-brown albite, white calcite, and green amphibole. Graphite is not uncommon, and large flakes of black mica—sometimes several centimeters in maximum dimension—characterize the coarser facies.

Pyroxene is scarce in the Bancroft area. A little diopside is almost invariably present in the coarse carbonate rocks, and deep-green pyroxene is occasionally of importance in members of the shonkinite group. But these enclosed lenses in the northern carbonate belt are the only rocks in which it is present in quantity.

Central or East Road Carbonate Belt.—This is the best exposed of the three belts and can be traced with slight interruption from a little west of Princess Quarry westward for about 2½ miles on either side of the East Road. Very narrow at its eastern end, it swells to the west, reaching a maximum width of at least 1000 feet just east of the gravel pit in Bancroft. Branching from the main belt at Colsen Lake, a narrow septum of marble passes due north, cutting directly through the ridge of alkaline intrusives and granite which overlooks the East Road. North of this ridge the carbonate rocks form a broad rocky pasture. To the west the marble narrows abruptly into a tapering sill-like wedge between the northern granite and the Copper Lake mixed-gneiss area. The marble-northern granite contact is nowhere well exposed. It passes through Clear Lake, and the stream which feeds into the lake from the west must lie about on the juncture. To the west the thin sill-like wedge of marble, like the slender Snow Road Valley tongue, gives way abruptly to coarse quartz-albite-aegirine pegmatite which has apparently been intruded along the marble-granite contact.

Westward from Colsen Lake the main carbonate belt contains occasional streaks of foyaite. Several of these have been trenched, and in one a quarry has been opened by prospectors for nepheline. A few hunderd yards west of Colsen Lake a slender peninsula of syenite-shonkinite juts out from the main intrusive mass into the marble. In Bancroft south of the East Road several lenses of granite lie in the midst of a poorly exposed foyaite-marble area. In a few places (*e.g.*, the hill just east of the gravel pit—Pl. 5, point A) excellent exposures demonstrate that similar granite bodies are enclosed in and cut by the marble.

The central carbonate band is lost beneath drift in the outskirts of Bancroft, but along the general trend of foliation of the westernmost outcrops carbonate rocks form islands in the York River. They are found again west of the York River as broad intercalations in the foyaites of the railroad cut in southern Bancroft and, finally, in the road cut and meadow just west of the Roman Catholic Church.

The rocks of this central carbonate band are without exception rich in enclosures of country rock and of various members of the alkaline complex. The commonest carbonate rock is a simple coarse-grained marble indistinguishable from the coarse white marble of the southern band or the Grenville marble south of the complex. Green diopside and black mica are almost invariably present, but the color index of the carbonate intrusive rarely exceeds 25. There are occasional lens-like bodies of practically pure biotite. Apatite is ubiquitous but rarely of quantitative importance.

Slender, feathery, blue-gray streaks of extremely fine-grained carbonate rock sometimes parallel the general foliation of the coarse marble in which they occur. In the field and under the microscope these have the properties of mylonite. The meadow opposite the Roman Catholic Church in western Bancroft is floored by fine-grained gray lime-mylonite. Large quantities of lime-mylonite are also exposed at Colsen Lake and at the intersection of the East and Clear Lake Roads.

The outcrops along the Clear Lake Road (Pl. 5, point C) are of particular interest since here the marble apparently cuts across the general foliation trend of the alkaline rocks. This is the narrow link which connects the Clear Lake marble area with the main carbonate belt. It lies between igneous rocks to east and west. The mylonite is most strongly developed precisely where the connecting link is narrowest—that is, where the cross-cutting relationship is most conspicuous. The effect is as of two great sheets of coarse white marble connected by a slender dike of lime mylonite. The easternmost exposure of the central carbonate belt is also a lime mylonite, in this case a dikelet cutting the shonkinite exposed in the road cut just west of Princess Quarry.

The coarse white marble is closely folded, but not so tightly as the puckered, crenulate mylonite. The silicates and apatite so characteristic of the coarse marble are absent from the mylonite. The large insoluble residue left behind when the mylonite is treated with acid consists chiefly of foreign enclosures.

Very few marble outcrops in the central belt lack inclusions, and in several places the carbonate rock is crowded with breccia "fragments" ranging from almost submicroscopic scraps to the mappable granite lenses already described. Some of the fragments are sharply angular, but most are rounded and elliptic.

Whether a particular fragment deflects flow lines or is itself folded is primarily a function of shape. Flow lines commonly wrap about equidimensional particles, while the more elongate fragments are themselves folded. Composition is of paramount importance in determining these dimensions. For instance, the schistose amphibolite readily splits into long, thin leaves. Flow lines in the marble are sometimes deflected by these amphibolite lenses. More often, however, amphibolite inclusions repeat in remarkable detail the folding of the marble in which they are enclosed. With increase of length these amphibolite breccia fragments pass insensibly into thin lenses or beds which might be considered original sedimentary impurities in the limestone. Flaky syenite, which often shows a pronounced parallel jointing in hand specimen, forms both nodules and flat bands which mimic crudely the folding of

the marble matrix. Despite its obvious mineral parallelism, the granite gneiss has a strongly interlocking texture and is free of any prominent fracture cleavage. It often forms elongate or lenticular masses in the marble. The continued and close folding undergone by the marble has even twisted and warped some of the more elongate granite inclusions (Pl. 2, fig. 1), but more commonly the granite is cut by numerous fractures filled with coarse marble.

In addition to the granite, syenite, and amphibolite inclusions, dense, black, chertlike fragments are common in the lime mylonite along the Clear Lake Road near its intersection with the East Road. Under the microscope these prove to be mylonites. No analyses were made, but from the recognizable perthite scraps which have survived it is fairly certain that these mylonite fragments were formed from syenite or quartz syenite. The syenite-mylonite fragments are sharply bounded, and flow lines in them do not parallel the flow lines of the lime mylonite matrix. In the same outcrop of lime mylonite there are numerous uncrushed syenite inclusions.

Fragments of coarse white marble are sometimes found in the lime mylonite, and at the Colsen Lake outcrop a large chunk of lime mylonite is enclosed in a matrix of the same composition. The boundaries of this fragment are clear and sharp.

A list of the inclusions found in the marble of this central belt reads like a catalogue of the rocks of the Haliburton-Bancroft region. Mylonite and marble fragments are confined to the lime mylonite. Granite is ubiquitous but it is commonest in the coarse marble. Of the alkaline suite, no shonkinite fragments were found, but the "end-members" of the shonkinite group—amphibolite and syenite—are among the commonest inclusions. *Only the nepheline-bearing rocks are unrepresented.* The recorded period of marble flowage and intrusion must therefore have followed the solidification of granite, amphibolite, and syenite and either preceded or accompanied the injection of nepheline rocks.

FINE STRUCTURE

Most of the true granites lack any conspicuous foliation, although careful inspection often reveals a rough mineral parallelism. The "impure" granites of the contact zones, contaminated with large quantities of hornblendic and micaceous material, are strongly banded hybrid-gneisses, consisting of elongate lenses, discontinuous streaks, and leaves of amphibolite enclosed in and injected by gneissic hornblende-biotite granite.

This foliated texture characterizes most of the syenites, all of the shonkinites, and all save the most pegmatitic of the nepheline rocks.

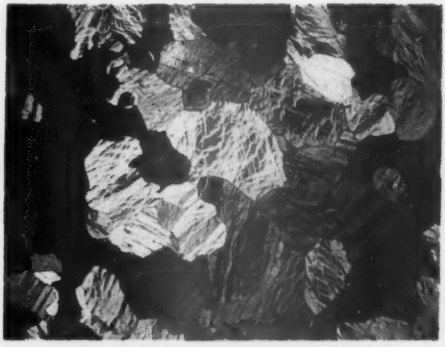


FIGURE 1. BRAID PERTHITE IN SYENITE
X-nicols. X 20.

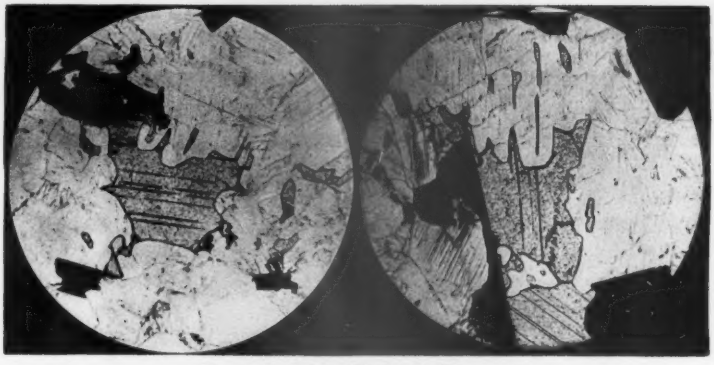


FIGURE 2. CALCITE REPLACING FELDSPAR
Plane light. X 50.

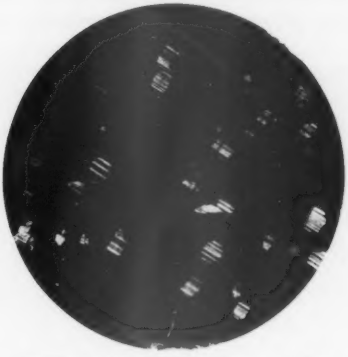


FIGURE 3. MULTIPLE-TWINNED "BLEB" PERTHITE, IN SYENITE
Section normal to *c*, X-nicols. X 50.

PERTHITE AND PRIMARY CALCITE IN SYENITE

FIGURE 1. SYENITE-MYLONITE FRAGMENT (left)
Enclosed in lime mylonite. Plane-light. X 12. Note that fold in lime mylonite is not duplicated by banding of syenite-mylonite fragment.

FIGURE 2. SYENITE-MYLONITE
X-nicols. X 30.

FIGURE 3. CONTACT OF SHONKINITE (left)
With dikelet of lime mylonite, X-nicols. X 15.

SYENITE-MYLONITE AND LIME MYLONITE

Marble too has strongly developed parallel fabric, expressed either by the banding of inclusions and dark minerals or by a rough slaty cleavage or parting.

In general, wherever the rocks of the region carry sufficient dark minerals they are visibly gneissic. Sometimes, as with the parting in marble or the alternation of feldspathic and feldspathoidal bands in foyaite, gneissic texture or at least a very coarse banding is well developed even in the absence of dark minerals.

Strike and dip of foliation vary widely and abruptly, small folds and crenulations are common, and flow lines invariably wrap about xenoliths. Foliation parallels all exposed contacts. Mortar structures are common in the contaminated granites of the contact zone and in some of the shonkinites and darker syenites, but there is no evidence of extensive mylonization or recrystallization of the eruptive rocks. All these properties are considered characteristic of primary gneisses; and, indeed, the presence of enormous quantities of perfectly fresh nepheline in some of the rocks almost precludes the possibility of any intense post-consolidation metamorphism.

Parallel orientation of the light minerals may very well be a primary flow structure in the sense of Cloos; but the conspicuous gneissic texture of the border granites, shonkinites, syenites, and foyaites is produced by the alternation of light and dark bands. These dark "bands" may be thin, drawn-out trains of separate crystals or clots, tapered, spindle-like streaks, bulging lenses, or persistent beds of remarkably uniform thickness. The larger dark masses are minutely dissected by thin seams, veins, and streaks of feldspar. Most of the dark bands represent previously existing metamorphic rocks which have been cut by and impregnated with the liquids which formed the alkaline rocks.

NATURE OF CONTACTS

In rocks of such persistently banded and gneissic habit discordant contacts would be immediately apparent. As in most pre-Cambrian terranes, however, contacts are almost exclusively concordant. In a few places very late acid pegmatite stringers and dikes transgress the foliation of shonkinite or amphibolite. Large outcrops of nepheline pegmatite or foyaite are sometimes criss-crossed by veins and dikelets of syenite. But clearly discordant contacts between representatives of any of the major intrusive types have not been observed. Where discordance seems implicit in the map, as at Colsen Lake, for instance, contacts are not exposed.

The concordant and conformable contact of one gneiss with another is rarely informative. There is usually a transition or mixed rock zone

in which both types are present in about equal proportions. (In the case of very abrupt transitions from granite through syenite into foyaite this is sometimes absent or insignificant.) Across the foliation in either direction one type comes to predominate over the other, the subordinate member appearing only as scattered lenses, streaks, and bands. These become less and less common away from the contact, and sometimes within a few yards, sometimes with a few hunderd yards, the contact zone disappears. Isolated patches of the subordinate member, whether intrusive or remnant, are occasionally found in the heart of the predominant type far from the contact zone.

The extremely rapid transition in which the mixed rock zone does not occur is well illustrated by the ridge south of the first nepheline quarry along the East Road, Bancroft (Pl. 5, point B) and by the granite-syenite (but not the syenite-foyaite) transition on the Goodkey farm northeast of Bronson (Pl. 5, point H). The more usual mixed rock zones are found south of Bronson on the Hawkins farm (Pl. 5, point G), eastward on the Carp farm, and westward along the road from Bronson to Bronson siding.

In extreme cases the mixed rock zone may be extravagantly developed at the expense of one or the other of the rocks involved in the contact. The large ridge between the Snow Road and the East Road in Bancroft (the Copper Lake area), for instance, consists chiefly of contaminated amphibolitic granite. But bands and streaks of syenite and shonkinite are exceedingly common throughout, so common that with better exposures several small syenite bodies might have been mapped. Yet, no large homogeneous body of syenite occurs in the entire ridge, and, as far as can be seen from the present outcrop, the syenites and shonkinites occur only as seams, lensed bands, and islands in the granite. The situation would probably be unchanged if the area were stripped of cover, for granite and quartz syenite occur along the southern crest of the ridge, overlooking the East Road, while along the foot of the ridge nepheline prospect pits have been worked at several points. This long ridge probably contains as much syenite as any comparable area in the entire map region. Yet the syenite "zone" proper is entirely missing, and its place is taken by an unusually large "mixed-rock" zone such as would ordinarily intervene between a fairly homogeneous granite mass on the one hand and a fairly homogeneous syenite mass on the other.

QUESTION OF SCALE

Adams and Barlow made no attempt to map syenite and foyaite under separate symbols, and of the area mapped by them as "alkaline and associated intrusives" at least a third and probably a half is underlain

by granites. This lumping of the entire alkaline complex under one symbol was a necessary consequence of the scale on which they mapped.

The same or a somewhat larger scale would have permitted the indication of a syenitic zone between granite and foyaite at several important localities. On such a map the syenite "zone" would surely be discontinuous in many places, exceedingly narrow in others, and in still others the dearth of outcrops would prevent accurate delineation. But if the investigation were carried no further a predominantly syenitic band between granite and foyaite could be at least diagrammatically indicated about two of the three large alkaline-intrusive areas—Bancroft and Tory Hill. It is hardly necessary to point out the inferences, gradational contacts, crystallization *in situ*, for instance, which could be quite legitimately drawn from a map showing such persistent if irregular zoning.

This zoning, like the localization of alkaline rocks along granite-marble contacts, is possibly of great importance, but its appearance on a geologic map is largely a function of scale. On a more detailed map bands and islands of syenite and amphibolite would appear within the granite areas; the syenite "zone" would be partly granite, partly shonkinite, partly foyaite; and in the foyaite areas would appear large patches and bands of marble as well as syenite, shonkinite, and a few streaks of granite. In addition, bodies of nepheline pegmatites would be shown completely enclosed in marble. The broad zoning of "pure" rock types would be replaced by a succession of mixed-rock zones in which now one type, now another, would predominate. Along the contact of one mixed-rock zone with another it would sometimes be necessary to show large bodies of acid-pegmatite.

All these complications have been indicated in Plate 5, which is a schematic key to the outcrops rather than an accurate geologic map. The rough grouping of mixed-rock zones is still evident, but there is no real symmetry governing the distribution of the rock types in detail, and truly gradual or gradational transitions would hardly be expected. The effect of the detailed map is thus precisely converse to that of the generalized description. Any satisfactory rationalization must be compatible with a zoning which is prominent, so to speak, in the hand specimen but virtually absent under the microscope.

PETROGRAPHY

GRANITE

The granites of the Haliburton-Bancroft region are usually gneissic, and in coarser varieties parallel structure is often preserved even where the total dark mineral content of the rock is very low.

The more clearly nonsedimentary granite gneisses are usually pink or red and, in the vicinity of Bancroft, are commonly rich in microcline or orthoclase with only occasional scraps of plagioclase and very little perthite. The granites studied by Adams and Barlow (1910) invariably carried oligoclase, and in some plagioclase was in excess of potash-feldspar. They give two analyses of typical red granite. In one there is almost as much soda as potash, and in the other soda actually exceeds potash. Their material was collected from the western and central portions of the field, and it is possible that the eastern granites differ considerably. For the present paper only granites in or near the alkaline belt were studied, and the bulk of the eastern granite probably corresponds more closely to the granites studied and analyzed by Adams and Barlow.

The commonest dark mineral of the granite is biotite. Hornblende is considerably less frequent. Even minute quantities of dark minerals often establish a fairly good lineation or foliation, and in the finer varieties this sometimes suggests a relict bedding structure. The dark minerals are most commonly found in clusters or streaky, discontinuous bands. Within these bands they may be randomly oriented. Well-defined single crystals of biotite or hornblende are rare. The granite usually contains very minor amounts of sphene, apatite, and zircon, and occasionally a little calcite.

A marked increase of either of the dark minerals is invariably matched by a decrease of quartz, and for this reason there are no true quartz diorites, granodiorites, or even dark granites, although the granite is often heavily contaminated with amphibolite. Even in the syenite group quartz occurs only in rocks of very low color index.

In the granites immediately associated with the alkaline rocks, anorthoclase is the most prominent feldspar. By decrease of quartz and increase of anorthoclase the granites pass into syenite. The perthites so characteristic of the syenites and shonkinites are absent from true granite but they are sometimes present in subacid anorthoclase granites. In general, rocks rich in perthite are not likely to be granite, while those poor in albite and perthite are not usually syenite. With regard to mineralogy and geology, any hard and fast distinction between quartz syenite and granite lacks both justification and utility.

AMPHIBOLITE AND PYROXENITE

This group includes the rocks of the remarkably persistent amphibolite ridge which bounds the complex on the south, the amphibolite streaks and bands scattered sporadically through syenite and impure

granite, and the pyroxenite lenses found only in the limestone of the Snow Road Valley.

The southern amphibolite ridge is composed of gneiss or schist of variable grain size. In coarser facies large pyroxene-hornblende intergrowths are set in a matrix of much finer plagioclase and hornblende. In medium- and fine-grained members pyroxene is absent. Scapolite is invariably present, sometimes to the almost complete exclusion of feldspar. Apatite and calcite are common throughout and particularly prominent in scapolite-rich rocks. Skeletal crystals of sphene occur occasionally, and there is also a little zoisite.

Pyroxene is always intergrown with a light-green, weakly pleochroic amphibole which may lie along cleavages or form clearly defined rims about it. Cleavage lines pass indiscriminately through the hornblende-pyroxene intergrowth, and, even where the rim of the crystal is hornblende, the aggregate retains the shape of pyroxene. As amphibole increases in amount, it is no longer confined to cleavages or grain borders but spreads haphazardly through the crystal, producing a vermicular intergrowth of about equal quantities of the two minerals. The amphibole may continue to increase at the expense of the pyroxene, forming perfect pseudomorphs, but more commonly an aggregate of amphibole and pyroxene or of amphibole alone either retains roughly the shape of the original pyroxene crystal or is strewn through the matrix.

The pyroxene has the optical properties of diopside with

$$2V(Z) = 62°$$
$$Z \wedge c = 39° - 44°$$

The amphibole is a tremolite with slight admixture of actinolite, with

$$2V(X) = 85°$$
$$Z \wedge c = 19° - 22°$$
$$Y = b$$

The fine-grained amphibole of the matrix has identical properties, but as the quantity of pyroxene diminishes the color of the amphibole changes from faint green to deep brown or green. Common hornblende is the amphibole of the pyroxene-free members.

Plagioclase varies from labradorite to oligoclase, the anorthite content varying directly with the total quantity of feldspar. It occurs as small laths or squares from 0.1 to 0.3 mm. in diameter, mostly untwinned. Parallel orientation of the laths is sometimes prominent, but more often the grains are not conspicuously elongate and no alignment is apparent.

Scapolite is present in every amphibolite slide studied. It is usually euhedral or subhedral, like the amphibole of the matrix, but may occur in fibrous veins or radially oriented aggregates. In quantity it varies inversely with plagioclase but only rarely can it be seen to replace that

mineral directly. Where scapolite is present only as a minor constituent, the plagioclase with which it occurs is andesine or even labradorite. Where the bulk of the light mineral content of the rock is scapolite, the plagioclase is oligoclase. A converse variation may exist in the scapolite but if so it must be much less extreme, for the interference colors of the mineral in slides of standard thickness never rise above yellow-orange and are usually only gray or yellowish-white.

In a specimen taken from the western end of the ridge, in Bancroft, there are remarkable vermicular intergrowths composed of about equal quantities of hornblende and pyroxene. In many grains the replacement of pyroxene by hornblende has been much more extensive, and sometimes only specks of a large grain retain the properties of pyroxene. In addition, small hornblende crystals are scattered through the groundmass. Yet the rock carries only a small quantity, perhaps a few per cent, of scapolite. In a specimen taken from an enclosure in flow marble at the eastern limit of the map area—just east of the York River crossing of the East Road—the opposite condition prevails. In this specimen large crystals of diopside are set in a matrix of subparallel scapolite laths, the flow lines established by the rough parallelism of the scapolite laths sometimes diverging about and sometimes terminating against the equidimensional pyroxenes. Though the substitution of scapolite for feldspar is nearly complete, the pyroxene transformation is only moderately developed. A few pyroxenes are extensively replaced, but in some only scattered flecks of amphibole lie along cleavages, and in still others amphibole is present only as thin and discontinuous mantles. No smaller amphibole crystals are present in the matrix. Specimens taken from streaks or bands enclosed in granite or syenite, however, sometimes consist entirely of scapolite and deeply colored hornblende. In none of these are there any traces of pyroxene, and the feldspar which is present in varying amounts is usually oligoclase. In these pyroxene-free varieties a little biotite (lepidomelane) is usually present.

Rounded grains of apatite are common throughout. They are often enclosed in hornblende or scapolite, rarely in plagioclase, and never in pyroxene. Calcite sometimes replaces feldspar or amphibole but it usually occurs in pockets of large grains whose relations to the other minerals of the slide are not clear. It rarely amounts to more than a few per cent and is sometimes absent. Both calcite and apatite are strongly concentrated in scapolite-rich members.

Lenses of pyroxenite occur in the marble of the Snow Road Valley. These consist in the main of green diopside and acmite-diopside, with variable but small amounts of honey-yellow albite. Calcite, sphene, and apatite are common. The pyroxene is usually rimmed and sometimes

extensively replaced by light-green, faintly pleochroic tremolite. Albite is concentrated in clusters which taper irregularly into narrow veins. In the finer-grained variety a little scapolite develops at the expense of albite. Flakes of lepidomelane, sometimes a few centimeters broad, are scattered throughout, and there are also occasional much smaller flakes of graphite.

SYENITES AND SHONKINITES

General statement.—The syenites and shonkinites—that is, the saturated or moderately oversaturated intrusives and hybrids—are the most variable of the alkaline rocks. They may be aplitic or pegmatitic and either strongly banded or unoriented. Many are tough, with closely interlocking grains. Just as many, though equally fresh, are powdery and practically incoherent, offering little resistance to the hammer and crumbling with careless handling. Color index is usually intermediate; but in many cases it is sensibly zero while in others it approaches 100. At first glance it would seem that such diverse rocks could have very little in common with each other and in fact they were mapped as a unit simply because nothing else was possible. At the same time it was recognized that the hybrid members are of two distinct types—one in which a solid feldspar rock was cut, injected, and enclosed by a basic intrusive, the other the much commoner variety in which the feldspathic material appeared to have been injected into a previously solid amphibole or biotite rock.

None of these rocks forms independent or homogeneous masses. The syenites occur chiefly in granite near amphibolite inclusions, and the shonkinites represent the further step in which syenitic liquid has soaked through and crystallized in amphibolite. In general a zone of these syenite-amphibolite-shonkinite migmatites lies between granite and the foyaite-carbonatite migmatites throughout most of the Bancroft and Tory Hill complexes. Adams and Barlow (1910) report a similar development of syenite and amphibolite in the margins of the Methuen batholith near its contact with the Blue Mountain foyaite, but there the relations are less clear.

The syenites and shonkinites formed by mixing of feldspathic liquid and solid amphibolite are characterized by potash-soda feldspars and perthite, often to the virtual exclusion of plagioclase. In the syenites and hybrids in which feldspar and feldspar-rock seem to have formed first, albite is dominant and potash-soda feldspars are represented sparingly or not at all. The potash-soda feldspar syenites or "potash-soda syenite-shonkinite" group and the plagioclase or albite syenites will be described separately.

Potash-soda syenites and shonkinites.—Rocks of this group, which includes most of the syenites and shonkinites, occur most commonly in granite near amphibolite bands or lenses. These amphibolite bands are often greatly enriched in feldspar, and the resulting hybrids are streaky, heterogeneous gneisses of shonkinitic composition. Sometimes the minute penetration of amphibolite by syenitic liquid has been forestalled by the development of major fractures along the amphibolite foliation, producing in place of shonkinite a coarsely banded composite of syenite and amphibolite. In either case the tremolite or hornblende of the amphibolite is transformed to a deep-green, strongly pleochroic and often opaque variety with which small quantities of pyroxene are frequently intergrown.

The sequence from granite through syenite into shonkinite is ideally demonstrated by outcrops on the Hawkins farms (Pl. 5, point G) southeast of Bronson, and along the road from Bronson to Bronson siding (Pl. 5, point DJ). The granite of the Copper Lake area, in Bancroft, is contaminated with innumerable small bands and lenses of amphibolite, and about these inclusions streaky syenitic gneisses are often found. Shonkinite rich in garnet and sphene is exposed on the East Road between Colsen Lake and the Princess sodalite quarry, and from here eastward to the York River crossing there are several excellent exposures of shonkinite, syenite, and quartz-syenite.

The rocks of this group vary so widely in texture that no generalizations can be made concerning grain size. Quartz-syenites are usually fine and aplitic, while quartz-free varieties are commonly coarse and pegmatitic. With increase of color index these extremes of texture are lost. In certain of the shonkinites clots of amphibole are enclosed in a feldspathic matrix and the resulting blotchy appearance suggests extraordinarily coarse grain. But the dark spots are actually aggregates of many finer crystals, and the grains of the feldspar matrix are not unusually large.

In color the variation is again so great as to limit the value of a brief summary. The soda-potash feldspar may be either red, pink, yellow-green, honey-yellow, or pure white. Pure white potash-soda syenite is known only from inclusions in the lime mylonite breccia. With increase of color index the feldspars lose their red and greenish tints, being commonly pink or honey-yellow and occasionally chalk-white. In hand specimen the dark minerals are almost invariably black, though biotite is occasionally deep green. All the minerals are uncommonly fresh. Feldspars often have a glassy luster, and the luster of amphibole is so high that the mineral is easily confused with mica in fine-grained specimens.

Syenite and some of the coarser shonkinite have a closely interlocking texture, but the average shonkinite is so powdery as to make trimming very difficult. Though perfectly fresh, some of the darker types crumble in handling, and one often wonders if some cementing material, perhaps calcite, has been leached out in weathering.

The principal minerals of the syenite-shonkinite group are alkali-feldspar, hornblende, and biotite. Rocks rich in both dark minerals do occur, but in general one is present in great excess of the other. In coarse syenites of very low color index biotite is the common dark mineral. It sometimes forms the bulk of rocks which for want of a better name would have to be called alkali-perknites. These are very rare, however, and biotite-shonkinites or even dark syenites are only slightly more common. Hornblende is the characteristic dark mineral of the potash-soda syenites and shonkinites. It is usually absent from the coarse pegmatitic syenites but it is the dominant and often the only dark mineral in the aplitic facies of the syenite as well as in most of the dark syenites and shonkinites. Quartz occurs only in aplitic hornblende syenites of very low color index. A little calcite may occur in any of the syenites, is invariably present in shonkinite, and may compose as much as 15% or 20% of the biotite-bearing varieties. Garnet, sphene, apatite, and zircon are concentrated in the dark syenites and shonkinites. Scapolite is occasionally present throughout.

The dominant feldspar of this group is perthite in which the host is usually anorthoclase, less commonly microcline, and rarely orthoclase. The distorted microcline-grid of the anorthoclase is sometimes almost submicroscopic. Crystals of this sort tend to have a wavy and incomplete extinction. Under crossed nicols they are often blotchy, and sometimes there is a more or less systematic "host-guest" relationship between areas of slightly different optical orientation. The boundaries between these blotches and the main mass of the crystals are always indistinct and usually jagged. Differences of refraction between the two phases are rarely great enough to give a reliable Becke line, and most commonly the crystals appear quite homogeneous in plane light. In strong contrast to these vague and indistinct blotches the truly perthitic albite has considerable relief against the anorthoclase host and usually shows somewhat higher interference color. Perthitic albite may form an interwoven mesh or braid in the anorthoclase or it may lie as plates or spindle-like rods along cleavages. Usually it also mantles the host. The crystallographic orientation of perthitic albite becomes less rigid as the ratio of albite to anorthoclase increases.

Similar perthites from Tory Hill have recently been described by Goldich and Kinzer (1939). There, as at Bancroft, the braid perthite

develops along the prism planes. Sections at a high angle to *c* give the effect of an interlocking meshwork of albite, while only parallel bands are shown by sections which include the *c* axis. The photographs given by Goldich and Kinzer clearly demonstrate that at least some of the perthite bands which lie in the (100) face are actually composites of the prism perthites. The coarse braids and the simple (100) bands are both common in the Bancroft syenites, but the curious superimposed prismatic braids lying in (100), as pictured by Goldich and Kinzer, are quite rare. Sometimes albite forms spindle- or pipe-shaped rods whose only crystallographic orientation seems to be a rough parallelism to the *c* axis. In sections cutting *c* at a large angle these appear as swarms of rounded or slightly elliptic blebs which are often polysynthetically twinned (Pl. 3, fig. 3). In perthites of all types albite may mantle anorthoclase or microcline, but only very rarely is the mantle of one grain continuous with that of an adjacent grain.

Of the other feldspars very little need be said. The plagioclase is almost always albite. A few grains with index higher than balsam were noted, and in the analyzed dark syenite feldspar in the immediate vicinity of garnet grains is sometimes as calcic as oligoclase-andesine. In many cases twin lamellae are extraordinarily narrow, and the same grain may appear sharply twinned in one part and homogeneous in another.

The amphiboles of the Haliburton-Bancroft region have been the subject of much discussion. The only chemical analysis available is that by J. B. Harrington, quoted by Adams and Barlow (1910, p. 247). Harrington's results were:

SiO_2	34.184
TiO_2	1.527
Al_2O_3	11.517
Fe_2O_3	12.621
FeO	21.979
MnO	.629
CaO	9.867
MgO	1.353
K_2O	2.286
Na_2O	3.290
Total water	.348
	99.601
Sp. Gr.	3.433

The water content is hardly that of a true amphibole, but Harrington states that this determination was simply an ignition loss, a method which can hardly be relied upon in the presence of so much ferrous iron. The ferric iron content is exceeded only in a few analyses of riebeckite. There is, in fact, far more ferric iron than would be required to accom-

modate the not exceptionally large alkali content. Ferrous iron is also very high, and magnesia remarkably low, as is the case with most of the rocks and minerals of the alkaline complex.

The amphibole of the alkaline rocks is deep green and often almost opaque in sections of standard thickness. Specifically:

X = Yellow-green to green-yellow
$Y = Z$ = Deep green or blue-green to opaque

Because of the very strong absorption of the mineral most of the universal stage measurements were made on extra thin slides with sodium vapor light. In these slides the very low birefringence of the mineral is troublesome. More than 50 grains were measured. In an attempt to eliminate the apparently random character of the results every measurement of which there was the slightest doubt was discarded. The 25-odd measurements remaining are hardly those of a clearly defined mineral species.

In every case Y lies along the b direction, and X is the acute bisectrix; $2V$ varies without any sharp break from 84° to 52°, and one very good measurement gave 40°. For optic angles between 64° and 84°, the values of $Z \wedge c$ fluctuate about 15°, a single value of 10° being the only one which departed from the mean by more than 2°. For optic angles between 40° and 64°, on the other hand, $Z \wedge c$ averages 23°. Four of the measurements gave the maximum of 24°, and it is possible that the lower values (20°, 21°) are in error.

On the basis of orientation of the indicatrix the results are divisible into two groups:

I. Deep green hornblende (black in hand specimen)	II. Hastingsite ? (black in hand specimen)
$2V(X) = 64°-84°$	$2V(X) = 52°-64°$
$Z \wedge c = 15° \pm 2°$	$Z \wedge c = 23° \pm 2°$
$Y = b$	$Y = b$

The orientation of the indicatrix and the optic angle of group I are the same as those of common hornblende and tremolite. When it is remembered that the color, absorption, and pleochroism of both groups are identical, that the most widely diverse measurements may come from a single slide, that the variation of the optic angle is completely gradual, and that the only sharp break in optical properties is a matter of no more than 12° and perhaps as little as 4° in the $Z \wedge c$ inclination, it will be apparent that there is very little basis for a sharp distinction between the common deep green hornblende of the area and the so-called hastingsite.

Adams (Adams and Barlow, 1910, p. 243) mentions that "two distinct varieties of hornblende, both green in color, could often be distinguished

in the same hand specimens", and one of these is presumably hastingsite. But the "hastingsite" described in detail by Graham (Adams and Barlow, 1910, p. 244) occurs as "small black individuals or aggregates". Amphibole is always black in the shonkinites and malignites, whether its optical properties are those of "deep green hornblende" or "hastingsite".

TABLE 1.—*Modes of typical syenites and quartz syenites*

	I	II	III	IV	V	VI
Quartz.....	0	9.1	11.4	18.6	22.8	26.4
Feldspar.....	99.5	89.4	88.1	80.4	76.7	73.1
Melanes.....	<0.5	<1.5	<0.5	<1.0	<0.5	<0.5

I. Syenite, Hawkins Farm, south of Bronson (Pl. 5, point G).
II. Quartz syenite, Snow Valley, Bancroft.
III. Quartz syenite, Churcher farm, Bancroft (Pl. 5, point B).
IV. Quartz syenite, Bronson (Pl. 5, point E).
V. Quartz syenite, Carp Farm, Bronson (Pl. 5, point I).
VI. Quartz syenite, East Road, near York River Crossing.

The green mineral of the late acid pegmatites and veins is usually aegirine or acmite-diopside, though sometimes amphibole.

Biotite is black or very rarely green in hand specimen and deep red brown to colorless in plane polarized light. Egleson's analysis of the black variety, quoted by Adams and Barlow (1910, p. 243), illustrates admirably the high ferrous iron (27.96% in this case) and remarkably low magnesia (2.99%) characteristic of the rocks and minerals of the field. The absence of both lithia and fluorine is surprising and may perhaps be questioned.

Pyroxene is deep green and less strongly pleochroic than hornblende, with

$X = Y =$ apple green
$Z =$ yellowish brown

The optic angle varies widely and unsystematically and may be either positive or negative, but the extinction angle $X \wedge c$ is less inconstant, ranging from 25° to 38° with an average of 30°. Where $X \wedge c$ is large, Z is the acute bisectrix. The mineral agrees most nearly with acmite-diopside, although the variation in optic angle is perhaps greater than is commonly found even in the alkali-pyroxenes.

In the quartz syenites and alkali-granites pyroxene is sometimes the only dark mineral; but in the dark syenites and shonkinites it invariably occurs with hornblende. Usually the proportion of pyroxene to hornblende is very small but occasionally—as, for instance, in the dark syenite analyzed—the two may be present in about equal quantities.

A little calcite occurs in most of the rocks of this group; and is particularly common in the darker members. In certain of the biotite-shonkinites, for instance, those exposed along the Colsen Lake-Clear Lake Road (Pl. 5, point C), it is a principal constituent, sometimes forming 20% or more of the rock. These rocks pass laterally into biotite-marble. The transition is rather abrupt but it can not be seen to be discontinuous.

TABLE 2.—*Modes of typical shonkinites*

	a	b	c	d	e
Feldspars (diff.)	63.3	53.9	48.5	40.5	29.9
Melanes (chiefly Hbl) (C. I.)	36.7	46.1	51.5	59.5	70.1

a. Analyzed shonkinite, East Road, near Princess Quarry (dark fraction discarded).
b. Shonkinite, East Road, 3 miles east of Bancroft.
c. Shonkinite, Hawkins Farm, commonest shonkinite in area (Pl. 5, point G).
d. Shonkinite, East Road, 3 miles east of Bancroft (Pl. 5, point D).
e. Shonkinite, East Road, 3 miles east of Bancroft (Pl. 5, point D).

Quartz is present in varying amounts in many of the aplitic hornblende syenites. Quartz-bearing syenites are invariably very poor in ferromagnesian minerals. The modes in Table 1 were determined with an integrating micrometer.

Apatite and sphene, though present throughout, are particularly concentrated in shonkinite and dark syenite. A little red or yellow-brown garnet may occur in any of the darker varieties but never rises much above 2% and is for the most part far less than this. Scapolite may occur in any of these rocks but, like nepheline, it is either present in considerable quantity or not at all.

The variation in color index is so great as to make impossible a representative sampling of the group. Heavy liquid separations were made on several hornblende-shonkinites, care being taken to exclude those unusually rich in garnet, sphene, calcite, and scapolite. The separations were clean, and the recovery usually 99.5% or better.

Since quartz is absent from all these dark rocks and garnet, sphene, and other minor minerals were held to a minimum, the color index determined by the heavy liquid separations gives a reasonably good approximation to the mode. The results are given in Table 2.

The combined light fractions and the combined dark fractions of the separations were analyzed, with the results shown in Table 3.

The perthitic nature of the feldspars which characterize the group is reflected in the light fraction analysis. The dark fraction illustrates

admirably the great preponderance of iron over magnesia. The analyses themselves represent the "end-members" of the potash-soda shonkinite group—syenite on the one hand, alkali-amphibolite on the other. By combining them in the proportions indicated by the color index the ap-

TABLE 3.—*Analyses of composite light and dark fractions of shonkinite*
(F. Chayes, analyst)

	Light fraction	Dark fraction
SiO_2	59.74	38.90
TiO_2	.....	1.14
Al_2O_3	19.28	9.92
Fe_2O_3	.....	8.18
FeO	.....	18.22
MnO	.....	3.00
MgO	.....	2.97
CaO	4.34	10.25
Na_2O	7.24	3.03
K_2O	5.19	2.18
CO_2	3.61	.....
$H_2O(+)$	.....	1.64
$H_2O(-)$	0.17	0.13
F	.....	0.07
	99.57	99.63
		O–F 0.03
		99.60

proximate composition of any specific member of the group may be obtained.

The commonest of the shonkinites, found in abundance along the southern margin of the Bronson granite and represented by *c* in Table 2, has a color index of 51.5 and a computed composition and norm shown in Table 4.

The rock consists of about equal quantities of hornblende and perthitic alkali-feldspar, with a few per cent of calcite and only trifling amounts of garnet, sphene, and magnetite.

The analysis of the dark fraction is very nearly that of a pure amphibole, with:

$$(Na\ K\ Ca)_{3.14}\ (Mg\ Fe\ Mn\ Al\ Fe\ Ti)_{4.86}\ (Al\ Si)_2\ Si_8\ O_{22}\ (OH\ F)_2$$

Thus, although the alkalis are only 5.21% by weight, the alkali-content of the formula is the maximum permissible. The excess of .14 atoms in the (*Na K Ca*) position is exactly compensated by the deficit in atoms of the *Mg* group. It may be that a little *Ca* or *Na* enters the second

group but it is more likely that the discrepancy is caused by a slight admixture of lime-rich minerals such as sphene, garnet, and acmite-diopside, the very small departure from the ideal formula indicating that these minerals are present only in minute quantities in the average hornblende syenites and shonkinites.

TABLE 4.—*Computed composition and norm of commonest shonkinite*

Composition		*Norm*	
SiO_2	49.3	or	21.7
TiO_2	0.59	ab	25.7
Al_2O_3	14.6	an	5.8
Fe_2O_3	4.3	ne	9.7
FeO	9.4	di	17.3
MnO	1.6	ol	9.2
MgO	1.5	mgt	6.3
CaO	7.4	il	1.2
Na_2O	5.1	cc	4.1
K_2O	3.7		101.0
CO_2	1.8		
F	0.04		
$H_2O(+)$	0.86		
$H_2O(-)$	0.15		
	100.34		

In the shonkinite just west of the Princess Quarry, sphene and yellow-brown garnet form skeletal crystals about very finely crushed aggregates of hornblende and feldspar. Except for this the rock is an ordinary, streaky hornblende-shonkinite or dark syenite. Its composition and norm are given in Table 5.

The femic content of the norm is 33.8 (including nepheline and anorthite as femic). A heavy liquid separation gave a color index of 36.7. The difference between this and the femic content of the norm may reasonably be assumed to represent the alkali and alumina content of amphibole and pyroxene. Because of its streaky and banded character and the very fine-grained hornblende-feldspar aggregates through which garnet is so irregularly disseminated, the rock is not suited for analysis with the recording micrometer. By this method even the color index could be determined only by measurement of many slides, and the estimates of garnet and sphene would be very poor approximations at best.

Field evidence suggests that the shonkinites of this group were formed by the injection of syenitic liquid into previously solid amphibolite. Hand specimens often provide additional evidence to this effect, and in the commonest shonkinite—the type which forms the southern margin of the Bronson granite area (*see* Tables 2C and 4)—clots of amphibolite appear to have been drawn out and suspended in a syenitic liquid.

Under the microscope the evidence is much less conclusive. The cores of amphibole crystals are usually solid, and the crystals may be euhedral. More commonly, however, the margins of the larger crystals are ragged, the outer fringes often being interstitial to near-by feldspars. Some-

TABLE 5.—*Composition and norm of sphene-and-garnet-rich shonkinite, just west of Princess Quarry*

(F. Chayes, analyst)

Composition		*Norm*	
SiO_2	51.51	or	56.7
TiO_2	0.98	ab	7.3
Al_2O_3	16.55	an	11.1
Fe_2O_3	6.98	ce	1.1
FeO	5.64	ne	1.1
MgO	0.39	di	6.9
MnO	0.14	wo	0.9
CaO	5.16	il	2.0
BaO	0.49	mgt	10.2
Na_2O	1.10	ap	1.0
K_2O	9.59	cc	1.1
P_2O_5	0.35		99.4
CO_2	0.47		
$H_2O(+)$	0.54		
$H_2O(-)$	0.26		
	100.15		

times a crystal with solid core becomes distinctly spongy or skeletal toward its margin. The amphibolites have evidently undergone a thorough chemical reorganization during the injection of syenite, and in places this reworking seems to have persisted after the crystallization of feldspar.

Of the principal minerals, biotite seems to be the earliest formed. Biotite crystals are often shredded and strained, and wedges of feldspar commonly penetrate along cleavages in the mineral.

Whenever present, quartz is late, invariably veining the principal minerals. Calcite is everywhere the last mineral to appear. It replaces feldspar in the fashion described by Bowen (1924) at Fen (*see* Plate 3, figure 2), leaving the dark minerals quite unaffected. Possibly the biotite "marble" along the Clear Lake Road has been produced by the substitution of calcite for feldspar. Only small patches of this rock are exposed. Although the near-by lime mylonite is rich in enclosures of syenite, coarse marble, and syenite-mylonite, it contains no fragments of the biotite-calcite-shonkinite.

Crush structures are well developed in many potash-soda syenites. Granular rims about feldspars are common, and it is impossible to determine with any certainty whether some of the finer-grained specimens

are aplites or crush-rocks. Fragments of syenite or quartz syenite-mylonite occur in the lime mylonite breccia (Pl. 4).

In several slides fibrous and micaceous aggregates are prominent. Most of these have the properties of sericite and are pseudomorphous after a mineral whose habit strongly suggests nepheline. In a few cases, however, the flakes which compose the aggregates have an axial angle of only a few degrees. In these rocks the aggregates are green, not only in the hand specimen but also under the microscope. They are probably talc. From the analyses of hornblende and biotite already quoted it is clear that talc could not form after either of these. The talcose aggregates may be pseudomorphous after diopside or olivine impurities derived from the adjacent marble.

Albite syenites.—In most of the potash-soda syenites a little plagioclase occurs, and in a few instances plagioclase is locally the dominant feldspar. Enrichment in albite is commonest in the vicinity of nepheline rocks. The syenites near the Snow Road foyaite-carbonatite tongue, for instance, carry considerable quantities of albite, but the mineral is much less abundant in specimens taken from the central portions of the Copper Lake area.

On the Hawkins farms, south of Bronson (Pl. 5, point G), a ridge of shonkinite and syenite forms the northern flank of the York River Valley. In the floor of the valley amphibolite, marble, and nepheline rocks are exposed. This is probably the best and most continuous exposure of syenite in the entire area. In an attempt to determine whether the foyaite-syenite transition was gradational, specimens were taken along a north-south traverse from the river to the crest of the ridge. No evidence could be found for a gradational contact. Although many lenses of acid pegmatite are exposed along the crest of the hill, and quartz syenite is common in the granite-amphibolite hybrids immediately to the north, the bulk of the syenite is apparently quartz free. Similarly, although schistose mica foyaite is exposed in the valley floor near the base of the ridge, and nepheline pegmatites are well developed in the marble immediately to the southeast, none of the syenites contain nepheline. Within the syenite, however, there is a distinct gradational relation between potash-feldspar and albite. Syenite along the crest of the ridge is practically devoid of albite. Specimens taken from the center and lower portions are rich in albite, and those taken from the base of the ridge, near the foyaite, are albite syenites carrying only small quantities of anorthoclase-perthite. There is no sign of an abrupt transition or, in fact, of any contact at all. The transformation is accomplished without conspicuous change in color, texture, or color-

index, and no relationship of this sort was suspected until the specimens were studied under the microscope.

The ridge immediately south of the first quarry along the East Road (Pl. 5, point B) consists for the most part of quartz syenite of the potash-soda type. This is everywhere separated from the foyaite which lies to the north by a curious hybrid consisting of granular, powdery albite-rock enclosed in a matrix of calcite-rich shonkinite and perknite. The flow lines of the dark matrix diverge about these boulders (Pl. 2, fig. 3) which in places are drawn out into coarse bands of albite. Sometimes single crystals or clots are strewn through the dark matrix which is often crumpled and folded in a manner matched elsewhere only by limestone. The whole southern flank of the hill is quartz syenite (10–15% quartz), and the shonkinite-albitite hybrid seems to form only a narrow zone between this syenite and foyaite. To the west the hybrid is lost under drift for a short distance, but along the strike shonkinitic gneisses reappear and then give way abruptly to coarse marble. It is this marble which has already been mentioned as containing twisted boulders of granite (Pl. 2, fig. 1). At about the middle of the syenite ridge it is possible to walk from pink syenite across the black and white hybrid and into gray foyaite in a distance of less than 75 feet without being able to place a single contact accurately.

The feldspar of the quartz syenite is almost entirely anorthoclase-perthite. The feldspar of the coarse powdery boulders is virtually pure albite, containing only 4% anorthite by universal stage determination. An alkali determination was run on this albitite, yielding:

K_2O	0.6%
Na_2O	10.42%

Although the evidence is far from conclusive, it is at least worth suggesting that the albitite has been formed by reaction between foyaitic liquid and solid syenite. The narrow bands of chalk-white albitite—usually only a few inches thick—which invariably separate foyaite from granite or syenite elsewhere in the area certainly formed in this fashion, and perhaps some similar explanation applies to the albite-rich "potash-soda" syenites found near foyaite or nepheline pegmatites.

NEPHELINE ROCKS

No detailed description of the distribution of nepheline rocks will be given since the main occurrences are fairly well indicated on Plate 5. Much of the nepheline rock has been indicated only schematically, and many smaller bodies are omitted entirely. All the important textural and mineralogical varieties are well represented at one or more of the mapped localities.

These rocks are frequently interbanded with syenite and often, perhaps most commonly, lie in marble a short distance from syenite or granite. They range from millimeter grain or less to the famous giant pegmatites of the York River in which single nepheline crystals up to a yard wide are not uncommon. Finer-grained varieties are considerably less common among the nepheline rocks than in the related syenites already described. In the eastern section of the field the nepheline rocks are never massive, but always banded or foliated.

Unlike the multi-colored feldspars of the potash-soda syenites and shonkinites, albite, the commonest and often the only feldspar of the nepheline rocks, is invariably white and usually chalky. Nepheline is usually grayish white or gray, and the common dark minerals, mica and hornblende, are black.

Most of the minerals of this suite are identical with those of the syenite-shonkinite group. The feldspars are the same, though they occur in very different proportions. Amphibole ranges in optical properties from "hastingsite" to green hornblende and cannot be distinguished from that of the syenites. The same black mica (lepidomelane) characteristic of the particularly coarse and leucocratic syenites is the commonest dark mineral of the nepheline rocks. Garnet is just as sparse in foyaite as in syenite and is important only in the York River migmatites, where it is red, in contrast to the brownish-black garnet of the analyzed shonkinite. Apatite, sphene, and magnetite are present in about the same quantities as in syenite. Zircon is important only in the pegmatites. Scapolite is less common in the foyaites than in the syenites.

Calcite is frequently present and always replaces feldspar, but its relations to nepheline are not clear. In nepheline-rich rocks it usually forms rounded grains, and where these lie in contact with nepheline a rim of cancrinite is often present. Sometimes veins or lenses of calcite lie parallel to the foliation of the nepheline rocks. Along the contacts with these veins nepheline crystals project, and specimens of the wall rock show euhedral nepheline crystals set in a matrix of calcite and apatite. The nepheline crystals are never found completely enclosed in calcite, and under the microscope the wall rock is neither particularly coarse nor calcite-rich.

The only minerals peculiar to this group are the feldspathoids—nepheline, sodalite, and cancrinite. Most of the nepheline is extraordinarily fresh. It is white or grayish white but, by the action of surface or ground water, it is readily converted to very fine-grained micaceous aggregates which may be white, red, or pale green. This alteration may be complete while the other minerals of the rock remain fresh. The mineral is often partially replaced by cancrinite, and in a few places

sericite pseudomorphs after nepheline are prominent. The nepheline of the York River pegmatites has long served as a mineralogical standard. Harrington's analysis is quoted by Adams and Barlow (1910, p. 236).

Sodalite is perhaps the best known of the Haliburton-Bancroft minerals, although it occurs in quantity only in the coarse pegmatites. It was analyzed first by Harrington and later by Leigher and Volckenning (Adams and Barlow, 1910, p. 239). The nepheline-rich foyaites often carry a little sodalite. The mineral is never euhedral, occurring almost always as a vein or fissure filling. In a few slides it is apparently pseudomorphous after nepheline.

Cancrinite is only rarely visible in hand specimen. It is citron yellow with a vitreous luster. (Earthy white varieties have been reported.) Under the microscope it commonly occurs in or about nepheline. Often a thin band of cancrinite lies between nepheline and calcite. It is occasionally euhedral and in such cases may be independent of nepheline. Whether euhedral or not, crystals of microscopic dimensions are often traversed by minute veinlets of sodalite. In the coarse pegmatites, however, cancrinite may replace sodalite.

The nepheline rocks range from foyaite and melanocratic hornblende-ijolite to urtite. In general all the other types seem to have been formed by the injection of urtite magma into previously solid amphibolite and syenite. The garnet-hornblende-nepheline rocks near Egan Chute, for instance, are migmatites produced by the injection of nepheline-pegmatites into garnet-amphibolite. The foliation of the migmatite is inherited from amphibolite, and all variations from alkali-amphibolite or perknite to urtite carrying only traces of garnet and hornblende can be collected within a few hundred feet of each other. In the near-by marble lie lenses of the famous coarse pegmatites composed of huge nepheline crystals enclosed in a skeletal matrix of feldspar. Ijolitic migmatites occur also where the southern shonkinite band is cut by the road leading from Bronson (Pl. 5, point F) to the railroad siding as well as in isolated patches of amphibolite near the Bronson schoolhouse. This last locality is well within the "homogeneous" granite of the Bronson area.

The schistose foyaite on the Hawkins property south of Bronson (Pl. 5, point G) has apparently been formed by injection of urtite into mica syenite. Here again, lenses of coarse nepheline-pegmatite abound in the adjacent marble. The foyaite of the Snow Road Valley, in northern Bancroft, consists of alternating folia of syenite and urtite. Away from the limestone contact the foyaite passes into syenite by an abrupt decrease in the frequency of urtite folia. South of the road the bulk of the rock is syenite, but here and there an eye or elongate lens of urtite parallels the foliation. Similar eyes and lenses are also found in the

foyaite proper (Fig. 2). This affords the most convincing evidence of the permeation of syenite by an urtitic liquid.

In a few cases—of which the exposures in western Bancroft will serve as examples—the composite origin of foyaite is not clear; but speaking

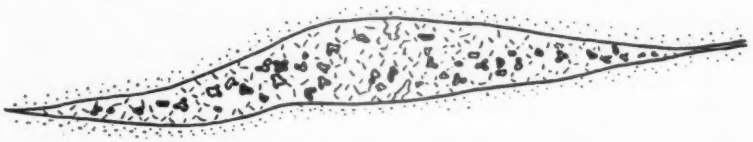


FIGURE 2.—*Urtite eye in foyaite, Snow Valley, Bancroft*
Black areas—calcite pits, areas of high relief—feldspar; remainder, nepheline.

generally there seems to have been no very large supply of foyaitic magma in the eastern portion of the field. This probably holds also for the Tory Hill complex and its satellites as well as for the isolated patches of nepheline rocks exposed between Tory Hill and Bancroft, but it may not be true of the Blue Mountain complex in Methuen.

Despite their composite origin the mineralogy of the nepheline rocks is fairly distinctive. Albite is invariably the dominant feldspar, and the anorthoclase-perthite characteristic of the syenites and shonkinites is present only in negligible quantities. Whereas hornblende is the common dark mineral of most of the syenite-shonkinite group, biotite is the typical dark mineral of the nepheline rocks. Hornblendic facies are rare and usually ijolitic in composition.

The common granulation and occasional mylonization typical of the syenites and shonkinites are almost never observed in the nepheline rocks. The only prominent exception occurs in sodalite-rich facies, in which sodalite seems to have been introduced along crush zones in urtite or foyaite.

LATE ACID PEGMATITES AND VEINS

Large masses of acid pegmatite have been intruded along contacts, particularly between marble and the other rocks of the complex. Most of these late intrusions are ordinary quartz-orthoclase pegmatites which may or may not be closely related to the alkaline rocks. Some, however, are rich in albite and aegirine.

A large mass of quartz-orthoclase pegmatite truncates the foyaite-carbonatite band exposed in the Snow Road Valley in northern Bancroft, and another large body lies along the southern margin of the Copper Lake granite area. Similar rocks occur in the syenite and shonkinite on the Hawkins farm (Pl. 5, point G) and also in the ridge opposite the Roman Catholic Church in Bancroft.

On the Carp farm east of Bronson (Pl. 5, point I), nepheline pegmatite is cut by quartz-tourmaline veins. Quartz and nepheline are always separated by a feldspathic zone of varying width. The nepheline-tourmaline occurrence on the York River at Egan Chute may be of this type. No quartz occurs here, but in the immediate vicinity of the large tourmaline vein by which it is cut the nepheline rock becomes exceptionally rich in albite and carries pockets of muscovite and orthoclase.

The peralkaline pegmatites and veins are much less common. The largest mass of albite-aegirine-quartz pegmatite lies along the Snow Road just west of Clear Lake. Smaller bodies are scattered throughout the field. A slender band cuts the foyaite exposed near the Roman Catholic Church in Bancroft. Green pyroxene is concentrated along the contact between pegmatite and foyaite at this locality. The center of the pegmatite band is rich in quartz, but toward the margins quartz falls off sharply, and at the contacts the rock is a quartz-free syenite. In the foyaite, on the other hand, nepheline pitting is well shown a couple of feet away from the pegmatite band, becomes less pronounced toward the contact, and finally disappears, leaving a zone of nepheline-free syenite a few inches broad lying against the pyroxene rim of the pegmatite. Were the pyroxene mantle absent it would be impossible to place the contact at all or even to distinguish syenite formed by this inverse "albitization" of quartz-pegmatite from that produced by silication of foyaite.

Quartz veins are common. Dark minerals in the granites and syenites adjacent to the peralkaline pegmatites are wholly or partly replaced by aegirine, which also frequently cuts these rocks in veins or veinlets ranging in thickness from the width of a knife-blade to a few inches.

The foyaite and urtite along the northwest border of the Bronson granite area are criss-crossed by numerous veinlets of white syenite. These are well exposed in the Vardy Quarry (Pl. 5, point EK), where they cut the foliation of the foyaite at a high angle. They may represent either a syenitic residue which has somehow escaped desilication or late acid pegmatite which has been "albitized" by the addition of solid alkalis and alumina in the same fashion as that exposed at the Catholic Church in Bancroft.

MARBLE AND INTRUSIVE CARBONATE ROCKS

In the gray and blue Grenville limestones biotite and quartz are the commonest silicates. In the coarse white Grenville marble tremolite is usually the principal noncarbonate. One of the analyzed specimens (4) carries a few per cent of deep-green spinel. In the coarse carbonatite of the alkaline complex phlogopite, diopside, and apatite are common,

and a little tremolite is sometimes present. Forsterite is quite uncommon. Pockets of yellow-brown garnet and green diopside occur in the marble along the York River near Egan Chute, and slides of this marble sometimes show aggregates of garnet and diopside a few millimeters wide.

The syenite and syenite-mylonite fragments in lime mylonite as well as the lime mylonite itself are pictured in Plate 5. The uncrushed-syenite boulders are often cut by coarse calcite which replaces feldspar. Many of the syenite fragments are granular and sugary, and in these large poikilitic tablets of albite are frequently developed. Amphibole or pyroxene veins sometimes lie along the contact between boulders and carbonate matrix, but any silicates which may have formed by reaction between the two have been swept away by the flowage of marble. The great number of perfectly clean and sharp contacts between marble and inclusions of all sorts (including quartzitic paragneiss and quartz-rich granite) implies that during the concluding stages of flowage at least, and perhaps for the entire period of marble intrusion, calcite and solid silica were in equilibrium.

No detailed geological study of the Grenville marble has yet been made, and until recently very few analyses were available. As part of a memoir on the limestones of Canada, Goudge (1938) recently provided many new analyses which show very clearly that most of the Grenville is comparatively pure calcite limestone. Magnesian facies are not infrequent but they seem to be distinct beds or bands rather than poorly defined zones, and no more a part of the limestone proper than are the interbedded slates and quartzites. In the Barker Quarry, south of Bancroft, for instance, the lime-magnesia ratio of one specimen was 1.69:1, and that of a second 75:1. From a single quarry at Bannockburn one specimen gave 1.77:1, and another 24:1. Again, from a quarry at Actinolite, the ratio in one specimen was 1.55:1, and in another 195:1.

The extent of dedolomitization and the control (if any) exerted by chemical composition upon carbonate flowage are matters of considerable importance in the present study. Specimens for analysis were chosen with these points in mind. The Grenville specimens analyzed by the writer are all from the Hastings Road section already described. From south to north, they are:

1. From the gray limestone at Millbridge
2. From a coarse white seam in the blue marble just north of Millbridge
3. From the blue marble several miles south of the Coe Hill turnout on the Hastings Road
4. From the white intrusive marble about 10 miles south of Bancroft (Pl. 1, fig. 2).

The remaining two analyses are of specimens from the central carbonate belt in the alkaline complex; 5 is of the coarse marble exposed along the East Road at Colsen Lake (Pl. 5, point C); 6 is from the lime mylonite along the Clear Lake Road near its intersection with the East Road (Pl. 5, point C).

TABLE 6.—*Analyses of carbonatite and Grenville marble*

	1	2	3	4	5	6
Insoluble.....	24.78	1.94	6.81	8.00	9.69	22.70
FeO.....	1.37	tr	0.47	0.94	0.77	1.21
MgO.....	1.75	1.20	1.73	2.15	0.40	0.64
CaO.....	39.10	53.29	49.20	48.50	49.90	41.75
P_2O_5.....	0.18	.....	.....	.....	.....	.10
S.....	.....	.....	.....	.....	.....	.31
Ignition loss...	31.91	43.30	41.44	40.47	39.34	33.14
($H_2O(-)$).....	.....	.....	(0.20)	(0.17)	(0.10)	(0.27)
	99.09	99.73	99.65	100.06	100.10	99.85

The large insoluble residue of the "unaltered" gray limestone (1) is principally mica with some quartz. On partial analysis it yielded 9.95% MgO, raising the magnesia percentage for the rock as a whole to about 4.2. In the blue marble (3) the residue is mostly quartz, with a little graphite and mica. In the white intrusive marble (4) the insoluble 8% is about two-thirds spinel, and the rest tremolite. Even assuming the entire residue to be a pure magnesia-aluminate, the magnesia content can be no more than 3.2% for the rock as a whole. In the lime mylonite (6) the large residue consists almost entirely of syenite and syenite-mylonite fragments, too small to be separated conveniently, but easily seen under the microscope.

Unless large quantities of magnesia have been extracted—and there is no reason to suppose that this is so—none of these rocks was ever more than very moderately dolomitic. All save one are "calcium-limestones" in the terminology of Goudge (CaO/MgO 10.5:1 or greater), and in this one the lime-magnesia ratio is 10:1.

There can have been no widely developed dedolomitization in the eastern part of the field because there seems to have been at best a limited and sharply localized supply of magnesia. Where magnesia was available, however, it was readily silicated. The famous "feather-amphibolites" of Adams and Barlow, practically pure tremolite-rock, are well exposed in the southern part of Dungannon Township. Granting a sedimentary origin for the southern amphibolite, its high magnesia content would be most readily explained by the assumption that what is now amphibolite was once a dolomitic band in marble.

In some of the carbonatites intercalated with foyaite, silicates—chiefly black mica—are concentrated along margins, while the centers are comparatively pure carbonate. These suggest very strongly an early dissociation and outward migration of magnesia. The mica of these rocks, however, is not phlogopite but a lepidomelane rich in ferrous iron and

TABLE 7.—*Soluble portion of marble analyses, computed to 100%*

	1	2	3	4	5	6	Pure calcite
CaO	52.6	54.5	53.0	52.7	55.2	54.3	56
MgO	2.36	1.23	1.87	2.34	0.44	0.83	.....
FeO	1.85	tr	0.51	1.02	0.85	1.57	.....
P_2O_5	0.24	.....	.....	.....	.....	0.13	.....
S	.....	.....	.....	.....	.....	0.40	.....
Loss on ignition, less moisture	43.0	43.3	44.7	44.0	43.5	43.0	44
CaO/MgO	22:1	44:1	28:1	22:1	125:1	65:1	.....

exceptionally poor in magnesia. (Egleson's analysis, cited by Adams and Barlow, 1910, p. 243.)

The paucity of magnesia is reflected by the dark minerals of the alkaline rocks themselves. Their abnormally high ferrous iron content involves and is perhaps made possible by an extreme scarcity of magnesia. In every one of the 12 "nepheline and alkali syenite" analyses given by Adams and Barlow (1910, p. 333) magnesia is less than 1.5%, in 11 it is less than 1%, and in 8 less than .5%. The shonkinites analyzed for this paper are similarly very low in magnesia, though in color index they are conspicuously higher than the rocks whose analyses are given by Adams and Barlow.

The source of the abundant iron which characterizes the alkaline rocks remains very much a mystery, for the removal of magnesia will not produce iron. But the mineralogical expression of ferrous oxide and the excess of ferric oxide over that required for the alkaline-amphibole and pyroxene molecules is probably controlled by the FeO/MgO ratio. Had there been a sufficient supply of magnesia either in magma or country rock large quantities of iron now locked up in hornblende and pyroxene would probably have appeared as ore.

Little can be said regarding the influence of chemical composition on carbonate-flowage. In Table 7 the soluble portion of each limestone analysis has been computed to 100.

The carbonate of flow marble does not differ in the slightest from that of the ordinary Grenville. The minimum magnesia content is that of

the coarse carbonatite within the alkaline complex, but the maximum is also given by an intrusive marble, in this case several miles south of the alkaline complex.

THEORETICAL CONSIDERATIONS

ORIGIN OF PYROXENITE AND AMPHIBOLITE

The pyroxenite lenses in the Snow Valley marble correspond closely to the metamorphosed marbles to which T. Sterry Hunt first applied the term pyroxenite. Unfortunately the nature of the amphibolites is not so clear. The southern amphibolite belt was not specifically mapped by Adams and Barlow. On the Bancroft sheet the Bancroft alkaline complex is bounded by "limestone and feather-amphibolite." On the Haliburton sheet the bounding rock appears simply as "limestone and associated gneiss or amphibolite."

The amphibolite is bounded on the south by the Grenville marble, and on the north a thin seam of marble everywhere separates it from the main mass of alkaline rocks. At its easternmost exposures, south of Bronson, it is cut by a little nepheline pegmatite. Farther east all the rocks are lost in thick swamp. The contacts of the southern amphibolite are nowhere well exposed, but its habit seems to be that of a conformable sill or bed. It never cuts the surrounding limestone, and in the few exposures available for study there is no gradual transition between the two. This absence of transition is of no great importance, however, since the marble is very probably intrusive.

The geology of the amphibolite belt is thus quite inconclusive. The amphibolites may be thermally metamorphosed sediments or intrusives or they may be silicated limestones. The fabric of the rocks has already been described and adds practically nothing to the discussion. In every case recrystallization is complete, and identifiable relict structures are absent.

Geology and fabric provide no answer, but mineralogy unfortunately gives more than one. Most geologists are skeptical of "contact limestones" composed primarily of hornblende and intermediate plagioclase, with only negligible quantities of calcite and no garnet, vesuvianite, epidote, or phlogopite. The common and perhaps justifiable tendency is to consider such rocks as thermally metamorphosed gabbro, diabase, or tuff.

There are, however, a few localities from which the large-scale generation of plagioclase in contact limestones has been described. Chief among these are Pargas, Finland, and the Haliburton-Bancroft region. Further comparison of these two areas will be required later, but here it need only be said that Laitakari's conclusions concerning the amphibo-

lites of Pargas agree very closely with those of Adams and Barlow. Adams and Barlow (1910, p. 157 *et seq.*) state that

"... field evidence (is) scarcely susceptible of any other interpretation than that, under the influence of the granitic intrusion, the limestone has ... been altered to amphibolite ... largely composed of feldspars, ... probably all plagioclase. The rock contains no calcite."

The amphibolites so formed contain between 50% and 67% feldspar, which varies from labradorite to andesine. Adams and Barlow were aware, of course, that this implies no mere silication of limestone but rather a complete "granitization," using the word to describe what is added rather than what is produced. They conclude that the

"... granite at first transfuses into the limestone silica, alumina, oxides of iron and magnesia, with some amount of titanic acid. ... In later stages ... the alumina, oxides of iron and alkalis are added in relatively greater proportion than the other constituents."

The net result of all these additions and transformations is that

"amphibolites originating in ... very diverse manners often resemble one another so closely that it is impossible to tell them apart ... when the origin of a body of amphibolite is not discoverable from its field relations, it is often impossible to determine whether it is an altered igneous rock or a body of altered sediment."

This is precisely the difficulty presented by the southern amphibolite ridge. Its fabric tells virtually nothing, its geology is inconclusive, and the mineralogy which most geologists consider the most reliable criterion is explicitly and pointedly discarded by Adams and Barlow. The implications of a possible igneous origin of the ridge will be treated where they are of greatest importance—in the discussion of the limestone-syntexis hypothesis.

SEPARATE MAGMA DEFICIENT IN SILICA

The quantity of alkaline rocks exposed in the Haliburton-Bancroft area cannot be accurately estimated. On the original maps of Adams and Barlow all "alkaline and associated rocks" were denoted by a single color. Of the 4000 square miles mapped by them less than 2% was demonstrably underlain by rocks of this group (Foye, 1915).

As shown on their map, the Bancroft area—about 15 square miles—consists of "alkaline and associated rocks" with the exception of two slender streaks of limestone. A large part of this area is underlain by granites of various sorts; another considerable portion contains only limestone or amphibolite. Using Plate 5 as a basis for rough calculation, nepheline-bearing rocks outcrop in or may be presumed to underlie something less than 15% of the area. Syenites, shonkinites, and quartz syenites occupy perhaps another 15%. Thus in this particular area a little less than 30% of the "alkaline and associated rocks" mapped by Adams and Barlow are actually saturated or undersaturated.

Applying this figure to the field as a whole, saturated and undersaturated rocks form about *six-tenths of one per cent* of all rocks present and about *one per cent* of all igneous rocks. Doubling, trebling, or quadrupling this figure cannot alter the fact that the magma of the undersaturated rocks was almost vanishingly small in comparison with that required for the formation of granite. It has been shown in this paper, under Late Acid Pegmatite and Veins, that solid nepheline has been readily converted into albite by the action of siliceous liquids and that quartz-alkali-feldspar rocks have been converted into albite and syenite by the action of magmatic liquids deficient in silica. A small quantity of undersaturated liquid introduced into such a vast volume of granite would have little chance for survival. It might produce occasional patches of soda-granite or syenite, but it is much more likely that it would simply disappear as a separate rock-forming fluid. Minute quantities of saturated or undersaturated rocks immersed in granite magmas of batholithic dimensions would be as readily digested and assimilated.

If the chance for survival of a foreign liquid or solid is small, there is even less possibility that a reservoir which has provided billions of tons of granite magma should suddenly and spontaneously give rise to sub-silicic magma and then just as suddenly and for as little reason revert once more to the generation of acid liquids.

We are forced to the conclusion that the undersaturated magma was in some fashion derived from the parent liquid of the granites and pegmatites with which the saturated and undersaturated rocks are associated.

ORDER OF INTRUSION OR SOLIDIFICATION

General statement.—Regardless of the particular stratigraphic terminology involved, it is generally agreed that the Grenville marble, the oldest formation exposed in the area, has been cut by the granites and hybrid gneisses called Laurentian by Adams and Barlow.

The contact amphibolites were shown by Adams and Barlow to have been produced by reaction between granite magma or its derivatives and limestone. Their formation requires either a granite magma or the fluid residue of such a magma, and they cannot very well post-date the existence of this liquid.

Throughout the field the alkaline rocks are marginal, lying characteristically between granite and limestone. In only one of these marginal bands—that at Blue Mountain, Methuen Township—are they massive and unoriented. In most cases their gneissic habit is admirably illustrated by hand specimens.

Syenite and quartz syenite of the potash-soda type are found primarily in granite near amphibolite inclusions. They are in fact nothing but marginal facies of granite. Shonkinitic hybrids result from the intimate mixing of amphibolite with syenitic liquid. The formation of shonkinite thus requires a pre-existent solid amphibolite.

The ferromagnesian minerals of the syenites, concentrated in sporadically distributed streaks and bands, are indistinguishable from those of shonkinite, and the feldspars of these rocks are identical. Every variation of color index has been found in the syenite-shonkinite group. What is true of shonkinite is almost certainly true of these closely related syenites and quartz syenites. The bulk of the syenites cannot be older than the granites whose margins they form.

The first phase of igneous activity, during which granite solidified, the reaction between limestone and granitic liquid produced amphibolite, and shonkinites and syenites formed in and about amphibolite enclosures in granite, was brought to a close by the extensive flowage and intrusion of comparatively unsilicated marble. For the most part the mechanism of this limestone flowage was merely an intensification of the ordinary processes of gliding, twinning, and recrystallization. In the sill-like bodies of coarse, complexly folded marble which were thus formed, inclusions of granite, amphibolite, and syenite are common. Nodular fragments of the coarse marble itself are occasionally found in lime mylonite, which thus represents the last manifestation of limestone intrusion.

No nepheline rocks were found as breccia fragments in these intrusive limestones. They are not so localized in occurrence as the members of the syenite-shonkinite group. They show no constant relation to amphibolite and often lie well within limestone. Granulation and mortar structures so common in the syenites and shonkinites are seldom found in the nepheline rocks. Discontinuous lenses and bulging spindle-shaped streaks of urtitic composition have often been injected into syenite; and it has been suggested under the heading of Nepheline Rocks that foyaite has been formed chiefly by extensive injections of this sort. For these reasons the nepheline rocks are assumed to be of later crystallization than the syenites and shonkinites. That they do not occur as breccia fragments in flow marble strongly suggests that they were still liquid during the period of carbonate intrusion. Geologically they are much more closely associated with carbonate rocks than with granite, syenite, shonkinite, or amphibolite, and it is possible that the "carbonate" intrusive was actually a sludge of solid carbonate lubricated by highly alkaline undersaturated liquids.

Where this sludge came in contact with granite or potash-soda syenite it produced the plagioclase syenites previously described. These exceedingly coarse, powdery albite rocks are sometimes found as boulders and lenses enclosed in a matrix of biotite and calcite. Where the inclusions lose their continuity and are strewn through the dark matrix a coarsely

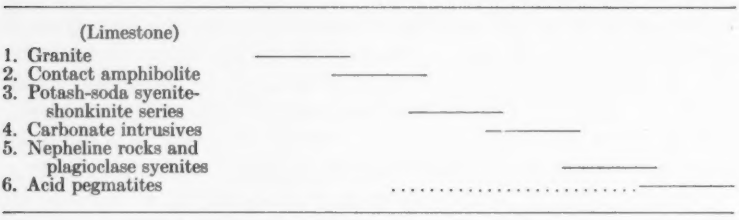


FIGURE 3.—*Time relations of major rock types*

banded shonkinite results. The relationship between light and dark minerals in the rare shonkinites of this type is exactly the converse of that shown in the much commoner potash-soda syenites and shonkinites.

Cutting foyaite and nepheline pegmatite are stringers of coarse quartz-albite-aegirine pegmatite which are usually about the composition of granite or more quartzose. The numerous veinlets of syenite common in some of the nepheline workings—particularly in the Vardy Quarry (Pl. 5, point EK), northwest of Bronson—may be the product of reaction between a nepheline-rich rock and very small quantities of highly silicic liquid. Larger bodies of acid pegmatite are found along marble-granite contacts and in syenite, but in general the larger the body the less clearly are its contacts exposed.

The intrusive sequence is summarized in Figure 3. The overlaps are not to be thought of as supported by the evidence but rather as possibilities not excluded by available information.

The abrupt and often discontinuous transitions between rock types and even between textural variants of the same rock make it convenient to speak of a sequence of "intrusion." It cannot be too strongly emphasized that what from one outcrop appears to be an order of intrusion is for the field as a whole only an order of solidification or consolidation of a single magma during a single major intrusion. The successive "intrusions" reflect only the changing character of the residual liquid and its included solids, whatever their origin.

This statement requires modification in one important respect. It is not suggested that all the shield granites of the area are products of a single magma or a single intrusion. They may and probably do represent

several intrusions. Each of these would be accompanied by its own pegmatitic residue, and any or all of them may have given rise to undersaturated rocks. Specific information concerning the number and relative dimensions of granite intrusions within the shield proper is lacking for this area, and the granites which by decrease of quartz pass into syenite and by increase of hornblende or biotite into shonkinite are indistinguishable from much of the shield granite exposed to the north.

Whatever the number of granite intrusions, the successive liquids injected into the crust were of almost identical composition. The parent magma of the alkaline rocks was a typical granite magma, high in silica and alkalis with a preponderance of potash over soda, low in iron, and practically devoid of magnesia and lime.

From the order of "intrusion" provided by the field evidence it must be concluded that as crystallization proceeded this granitic liquid gradually lost its large excess of silica, becoming finally strongly undersaturated and highly sodic. After solidification of the undersaturated residue small quantities of acid pegmatite were injected.

Comparison with previous results.—Adams and Barlow (1910) suggested that the large granite and quartz-syenite bodies at Blue Mountain in Methuen Township and near Egan Chute in Dungannon Township were younger than the nepheline rocks of these localities. From a study of the Blue Mountain intrusive Keith (1939) has recently come to the same conclusion. He feels, furthermore, that this is the common relationship throughout the field. His statement of age relations is based partly on helium-ratio determinations made by Keevil. Strictly interpreted, these determinations make the foyaite ("leucolitchfieldite" of Keith) early or middle pre-Cambrian, the mafic fraction of the syenite late pre-Cambrian or early Paleozoic, and the felsic portion of the syenite Paleozoic or later. Keith and Keevil admit that their results are not accurate insofar as absolute ages are concerned but they feel that relative age relations are properly represented. Even this may be questioned, for the determinations were made neither on single crystals nor even on single minerals but on bulk samples of rocks of variable composition and texture. Radioactive minerals are exceedingly scarce in all the analyzed material, and the variation of helium-ratio may reflect a change of grain size, of fabric, or of composition rather than an age difference. Hurley and Goodman (1941) have recently shown that the helium method is unreliable for direct analyses on rock samples.

Acid pegmatites were injected into alkaline rocks of all types, and the continuing existence of an alkalic but nevertheless oversaturated rock liquid is an important feature of the discussion immediately following.

With such a liquid available large-scale intrusion of granite after the formation of the undersaturated rocks is unquestionably possible.

In the Bancroft area there is no evidence of any large granite intrusion later than the nepheline rocks. Adams and Barlow thought that the lenticular syenite-granite body exposed near Egan Chute had been intruded into the slender ring of nepheline rocks which surrounds it. Contacts are nowhere observable, and even the best evidence is indirect. In this and similar granites and quartz syenites granulation is frequently encountered in thin section. Pseudomorphous aggregates composed of talc or muscovite have been found in several specimens. Quartz, despite its very late crystallization, is invariably strained and frequently shattered. Yet in the ijolites, jacupirangites, and nepheline-pegmatites presumed to have been cut by this granite, nepheline is clear and fresh. Only the sodalite facies shows any conspicuous granulation, and this is related to the formation of sodalite and therefore unrelated to the granite intrusion. The nepheline is not only fresh and unaltered but also markedly euhedral in the coarser pegmatites and in general so little strained that it often shows no cleavage even in thin section.

Nothing final can be said concerning the Blue Mountain complex until the associated granites and syenites are more fully described. The occurrence is in many respects unique, and conclusions based on other portions of the field may not be applicable.

Barlow's descriptions of the Craigmont area (Adams and Barlow, 1910) mention syenite, corundum syenite, and acid pegmatite cutting nepheline rocks. As at Blue Mountain, no final conclusions are possible without further knowledge not only of the nepheline rocks but more particularly of the associated granites and syenites.

The geology of the Tory Hill complex is very similar to that of the Bancroft area. Here once more, if Keith's view is correct, a lenticular mass of granite must have been intruded into a thin surrounding shell of nepheline rocks leaving the nepheline of the older, strongly undersaturated rocks chemically and physically intact. Here too, pseudomorphous aggregates of muscovite, apparently replacing nepheline, are conspicuously developed in the supposedly younger syenites.

For the field as a whole—with the possible but improbable exceptions of the Blue Mountain foyaite mass and the Craigmont occurrences—alkaline rocks are younger than the bulk of the granites but may themselves be succeeded by small quantities of acid pegmatite. In the eastern portion of the field the syenites and shonkinites formed during or immediately after the consolidation of granite, and the nepheline rocks are slightly but distinctly younger than syenite. The sequence as developed from study of the Bancroft area may be safely extended to include the

Tory Hill complex and its pegmatitic satellites, as well as several smaller and poorly exposed bands lying between Tory Hill and Bancroft.

From lead-uranium ratio determinations on radioactive minerals Ellsworth (1921; 1922) placed the syenite pegmatite of Wilberforce and the granite pegmatite of Hybla in the early pre-Cambrian. Both these pegmatites cut granite which in turn cuts the Grenville limestone. The alkaline intrusives, the late acid pegmatites, and probably all the rocks of this portion of the shield are early pre-Cambrian.

ORIGIN OF THE ALKALINE ROCKS

Whenever present, quartz is a mineral of very late crystallization. In granite it sometimes encloses and always either cuts or is interstitial to feldspar. The same relation holds in the quartz syenites. The pegmatites, and particularly those pegmatites younger than the nepheline rocks, are often far richer in quartz than the average granite. It can only be concluded that the magmatic residue became increasingly siliceous as crystallization progressed. Yet sometime during its consolidation, and preferably toward the close of crystallization, we must derive from this magma a quantity of less silicic liquid capable of forming the saturated and undersaturated rocks of the region. How can the increasingly siliceous residue of a granite magma give rise to undersaturated rocks?

Several explanations and partial explanations have been offered, and since none of these is likely to prove completely satisfactory each will have to be weighed separately against the relevant field evidence. The suggestions which merit attention include the pseudo-leucite hypothesis of Bowen, the limestone-syntexis hypothesis of Daly, Smyth's concept of the crucial significance of volatiles, the possibility of amphibolite assimilation, and the "alkali-emanation" hypothesis of Wegmann and Holmes. The discussion follows what the author considers an order of increasing probability.

There is only one prominent advocate of the view that alkali-magmas are *destroyed* by assimilatory processes. This is precisely the opinion of Wegmann (1935), who says (in translation) that alkali-magmas ". . . appear as rocks only under particular conditions, specifically, if in their paths they cut no rocks which can draw from them a great portion of their alkali content . . ." A somewhat similar position is taken by Holmes (1937). The withdrawal of alkalis, Wegmann holds, is most readily effected by the sediments and greenstones of the great geosynclinal troughs, and alkaline rocks thus form only along the gently sloping continental margins of the geosynclines. Since this is where limestones also occur, the association of marble and foyaite is fortuitous.

Granting that the alkaline belt lies along a granite-marble contact

which may represent the continental margin of a geosyncline, and overlooking the hypothetical and unlikely composition of the magma involved, it can still be shown that the syenites and shonkinites are derived from the same magmas which produced the granites of the area. Few will suggest that the close association of nepheline rocks with syenite and shonkinite in this area is fortuitous. Wegmann must thus explain not only foyaite, but syenite, shonkinite, and granite as well. Here the evidence fails.

For the pseudo-leucite hypothesis of Bowen (1928, p. 253) there is no field evidence. Nothing resembling leucite or pseudo-leucite has ever been reported from the region, the feldspar which accompanies nepheline is generally albite, and the potash-rich feldspars, which in Bowen's view should form simultaneously with nepheline, occur in quantity only in syenite, shonkinite, and granite.

Smyth (1913) and others have placed strong emphasis on the transport of alkalis and iron by volatile and fugitive constituents. The principal dark minerals of the alkaline rocks—mica and hornblende—are hydrous and the concentration of fugitive constituents is unquestionably high in certain facies of the foyaite and syenite. But the saturated and undersaturated rocks are certainly no richer and may be considerably poorer in these constituents than are the acid pegmatites of the northern granite area—for instance, the famous Wilberforce, Hybla, and Quadville deposits. The "mineralizers" may have been of considerable subsidiary importance in determining the fabric, habit, and mode of occurrence of the alkaline rocks; but the field gives no evidence that by their activity an oversaturated magma has either been deprived of excess silica or has yielded a separate alkaline fraction.

Bowen (1928, p. 269) has suggested that the resorption of early formed amphibole crystals by basaltic magma results in the precipitation of olivine and the simpler pyroxenes and enriches the (lamprophyric) liquid residue in alkalis and iron. Is it possible that once amphibolite had been formed—by whatever means—a further reaction between magma and amphibolite produced alkaline magma ?

The only available magma in this region is granitic rather than basaltic, and the amphibole of the amphibolites is commonly tremolite. In addition, amphibolite in contact with syenite is invariably enriched in both iron and alkalis. Instead of a reaction between granite and amphibolite to produce syenite there is evidence only of a reaction between syenite and amphibolite to produce shonkinite. At the present erosion level the amphibolites are more important for what they have withdrawn from the magma than for what they have contributed to it; and the principal constituents withdrawn—alkalis and iron oxides—are

precisely those which should have been added to the rock liquid by assimilation of amphibole.

Daly (1910; 1914; 1918) has long maintained that saturated and oversaturated magmas could be desilicated by reaction with limestone, the resultant liquid forming feldspathoidal rocks. In Daly's original hypothesis superheated basalt was favored as a parent-magma. But in most cases foyaites and syenites have proved to be associated with granite rather than basalt, and in his most recent statement of the hypothesis Daly (1933) concedes that foyaitic and much syenitic magma must be derived from granitic liquid.

Even the strongest opponents of assimilation must admit that the general geology of the Haliburton-Bancroft field is favorable to the limestone-syntexis hypothesis. The alkaline rocks lie in a broad zone formed by the irregular contact of granite and limestone. Toward the contact the limestone becomes coarser and more heavily silicated. Within granite, limestone inclusions are scarce, but amphibolites are remarkably common. Sometimes it is possible to trace the alteration of limestone into amphibolite, but more commonly the transition is quite abrupt, limestone extending to the granite boundary and amphibolite lying within the granite. The contact origin of most of these amphibolites is generally admitted.

Let us return to the question of the origin of the amphibolite band which forms the southern boundary of the Bancroft alkaline complex. This amphibolite is completely isolated in marble, and its production by contact action would be not at all a matter of the desilication of granite magma but rather of the wholesale transfer of a portion of granite magma from magma chamber into wall rock. It need not be assumed that the numerous amphibolite lenses in granite are of igneous origin merely because the southern ridge may have been gabbro rather than limestone. It is possible that the hornblende-plagioclase-scapolite gneisses of the alkaline complex proper are closely related to the southern amphibolite—in fact, this was tacitly assumed in the petrographic descriptions of these rocks. But the alkali-amphibolites and shonkinites invariably carry a little garnet and are often rich in calcite. Instead of the puzzling andesine of the southern amphibolite they carry only alkali-feldspar which has been injected into them. Some of the alkali-amphibolite may be nothing but altered gabbro along whose contacts with granite syenitic liquids have penetrated most easily; but this cannot be proved in a single instance.

Judging by its solid equivalent the granite magma of the area must have been rich in alkalis, low in iron oxides, and practically devoid of lime and magnesia. For the production of syenite and syenite-magma

from such a liquid only the removal of magmatic silica is necessary. What more direct explanation can be offered than the suggested reciprocal relationship between the silication of marble to form amphibolite and the desilication of granite magma to form syenite? This explanation is supported not only by the geology of the rocks concerned but even more strongly by their mineralogy.

For the granite-syenite-shonkinite association the limestone-syntexis hypothesis provides the most satisfactory single explanation. With regard to the reaction between amphibolite and syenite-liquid the theory in its present form is incomplete. It is easy to derive a highly alkaline liquid from granite-magma, granted the suggested method for the removal of silica. But what is the source of the great quantities of iron oxides which have been added to the amphibolite in the formation of shonkinite?

The only answer is that there is no known source. The limestone is poor in iron. The granite is also low in iron, and if all that is involved in the production of syenite magma is a subtraction of silica from granite magma, the iron content of the syenite liquid would not have been much higher than that of the granite. Yet the shonkinites are characterized by large percentages of both ferric and ferrous oxides. The amphibole of the shonkinites has been thoroughly reworked by the magmatic residue after the crystallization of feldspars was well under way and perhaps after it was completed. The little iron present in the original granite magma would have been relatively increased, first by the removal of magmatic silica and then by the crystallization of feldspar; but it would still be only a little iron.

The evidence is limited and inconclusive, but it should be mentioned that in the predominantly tremolitic amphibolite of the southern ridge there are occasional hornblendic pockets and bands, and it is in these that scapolite, apatite, and calcite are most heavily concentrated. Hornblende-scapolite gneisses also occur interbanded with shonkinites and syenites, and in a few cases a biotite-scapolite-plagioclase gneiss appears to be cut by syenite. In effecting the increase of total iron, mineralizers may have been of considerable importance as transporting agents; but they appear to have had no effect either on the soda-potash ratio or on the silica saturation of the magma.

The concentration of iron in alkaline magmas is in a sense outside the immediate province of the limestone-syntexis hypothesis; but with regard to the nepheline-bearing rocks the hypothesis must either apply or be declared invalid. Of the close relationship between nepheline rocks and the syenite-shonkinite series there can be no question. It can hardly be that one group is of assimilatory and the other of non-assimilatory origin. Nothing in the field relations or mineralogy of the nepheline

rocks is inconsistent with the demands of the limestone-syntexis hypothesis. Yet the rationalization made possible by the hypothesis is fragmentary and lacking in detail. It is difficult to decide whether the theory is incomplete or the exposures are insufficient.

The nepheline rocks generally carry albite as the dominant or only feldspar. Their dark minerals are the same as those of the syenites and shonkinites, but there is no general tendency toward an even balance of light and dark constituents. In fact, nepheline rocks rich in feldspar are very likely to be rather poor in dark minerals, while conversely melanocratic nepheline rocks are poor in plagioclase. This inverse ratio between feldspar and dark minerals is by no means sharp and clear cut. It holds fairly well for hornblende-bearing varieties but is less valid for biotitic facies.

There seems to have been only a limited supply of foyaitic magma throughout most of the region. Nepheline-rich liquids of urtitic composition have been injected into the various rocks of the complex. Where syenites were invaded, foyaites were formed; where amphibolites were cut, ijolite and jacupirangite resulted. Urtitic liquids do not seem to have been injected into shonkinite.

The assumption that the urtite magma was simply the residual liquor strained from the shonkinites permits a synthesis of many apparently unrelated scraps of evidence. It suggests an explanation for the granulation and occasional mylonization of syenite, the absence of such phenomena in foyaites and urtites, the scarcity of shonkinites poor in nepheline, the prevalence of nepheline pseudomorphs in these nepheline-poor shonkinites and syenites, the random distribution of nepheline rocks with regard to earlier members of the intrusive complex, and their very close association with marble. The moderate dynamic metamorphism required for the separation of urtite residue from solid shonkinite would have occurred at about the time that marble flowage reached its maximum.

For the most part these are matters of slight importance, and although the fact that they are all rationally explained by the assumption may be regarded as supplementary evidence it surely cannot be called proof. Although the details of the formation of urtite liquid are not clear there is enough independent evidence from the granite-syenite and amphibolite-shonkinite relationships to create a strong presumption in favor of limestone-syntexis. The explanation offered by Daly's hypothesis is once more the simplest and most direct. More precisely, Daly's hypothesis contains at least the possibility of an explanation, while for this specific case the other theories discussed fail to meet the demands of the field evidence.

Only the very late albite-aegirine-quartz pegmatites have not yet been fitted into the theoretical framework. On the Wegmann-Holmes hypothesis a palingenic acid-pegmatite might form by the interaction of siliceous sediments and primary alkaline fluids. But it could not persist as a liquid after the crystallization of these alkaline fluids; in fact, it could not form except by exhaustion of the parent liquid, and it should not occur in association with undersaturated rocks, which represent an excess of alkaline fluid over available solid silica. The pseudo-leucite hypothesis of Bowen takes as its starting point a highly potassic granite magma from which most of the excess silica has already been removed and could therefore provide no source of acid pegmatite after the completion of the pseudo-leucite reactions. The agency of volatiles in concentrating alkalis and desilicating granite magma was dismissed because of the high concentration of the mineralizers in these acid pegmatites.

The acid, and particularly the peralkaline pegmatites, are as nice a demonstration as could be desired that here, as elsewhere, a granitic magma under plutonic conditions becomes more and more siliceous with cooling and crystallization. There is a very real concentration of soda as opposed to potash, and there is also an increase of iron oxides. But dwarfing both of these is the concentration of silica in the liquid residue. It may be concluded that the self-contained and routine crystallization of granite magma could have produced neither feldspathoidal rocks nor undersaturated liquids. For the production of these some special agency is required, and in the Haliburton-Bancroft field that special agency seems to have been limestone-syntexis.

But can the limestone-syntexis hypothesis itself be reconciled with the existence of these late acid pegmatites? The argument proceeds from ignorance rather than knowledge. The acid pegmatites are found not only along the margins of the granite but are in fact far commoner in the interior. The nepheline rocks, on the other hand, occur only in the immediate vicinity of the contact. The pegmatites surely cannot be *produced* by limestone-syntexis. They exist rather in spite of assimilation and that they persisted as liquids after the nepheline rocks had formed implies that the assimilatory reactions were limited to the period following the consolidation of the margins of the granite but preceding the final solidification of the interior of the mass.

Excepting the unexplained enrichment in iron oxides, the principal geological objections to the limestone-syntexis hypothesis are physical. The abrupt and sometimes discontinuous transitions from granite to syenite or syenite to foyaite reflect only the continual relative movement of rock and magma. The fact that marble silication does not vary gradually and progressively across the strike of the beds is readily explained

by the intrusive character of unsilicated carbonate rocks. The intrusion of acid pegmatites into nepheline pegmatites shows that whatever assimilation occurred was limited in both time and place, but it does not show that assimilation did not occur. These are all physical arguments directed against a chemical and mineralogical theory. They render an exact demonstration impossible and they can limit the value of positive evidence but they do not in themselves constitute negative evidence.

It would be convenient if all the rocks were symmetrically distributed, if all transitions were completely gradational, or all contacts sharply discordant. But if these conditions are not realized it will not be fatal to an argument for which they are means rather than ends. The final criteria of a mineralogical argument are minerals, mineral assemblages, and mineral relations. On the whole, the mineralogy of the Haliburton-Bancroft field favors the limestone-syntexis hypothesis and provides no positive evidence for any other theory.

PRIMARY CALCITE AND INTRUSIVE CARBONATE ROCKS

There is no evidence for a carbonate magma, if by the term magma a true fluid or liquid is implied. It has been shown that during much of the period of carbonate flowage calcite and quartz were in equilibrium. Although diopside is common, no wollastonite has been found. Thermal metamorphism is thus of intermediate grade at best. The close folding, crenulation, and flowage about inclusions so well shown by the carbonate rocks within the alkaline complex are found over and over again in the Grenville marble to the south. The intrusive character of marble is nowhere better displayed than in the road-cut shown in Figure 2 of Plate 1, 10 miles south of Bancroft. There is no significant chemical difference between the carbonate of the Grenville proper and that of the "carbonatites" in the alkaline belt. The coarse marble of the alkaline belt is undoubtedly a part of the Grenville marble.

How, then, has it been intruded? To this question there is no precise answer. Possibly tongues of the southern Grenville have broken through the bounding amphibolite at depth. But lenses of marble occur also a few miles north of Bancroft, at Bird's Creek and Hybla, and isolated masses are scattered through the northern granites. As each of these is considered a large-scale intrusion of marble into the granitic and alkaline rocks becomes less and less plausible.

It is much more likely that the marble bands were originally enclosed in granite by infolding, stoping, or flotation. A subsequent deformation such as that which produced the granulation and occasional mylonization of syenite and quartz syenite might then produce flowage in marble, with the result that fragments of amphibolite, granite, and syenite are now

enclosed in marble. Crevices opened by the fracturing of brittle rocks would be filled by flow-marble, the final product being in some cases indistiguishable from vein calcite. Large granite boulders enclosed in carbonatite often show filled-in fractures of this type.

The mylonization of the intrusive marble was apparently confined to the central carbonate belt. Streaks of mylonite are scattered randomly in the coarse marble of this belt, and large masses of mylonite occur at both ends. Whether there was more than one period of lime mylonization is not clear. Between the nepheline-amphibolite-migmatite and the coarse nepheline pegmatite of the Morrison quarry, northeast of Egan Chute, lies an exceptionally fine-grained diopside marble. Throughout the central carbonate belt a thin fringe of coarse white marble often separates mylonite from enclosed syenite or granite. In such instances the coarse marble may have been formed by a post-flowage, *in situ* recrystallization of mylonite.

The meadow opposite the Roman Catholic Church in Bancroft is floored by gray lime mylonite, but a broad band of coarse white marble separates it from the syenite-foyaite ridge to the south. Here the syenite can hardly be an inclusion, and the relations do suggest that an early formed mylonite has been recrystallized. The syenite ridge itself, however, is cut by acid pegmatites, and the recrystallization may be due to the heat and moisture attendant upon the intrusion of pegmatite rather than syenite. Somewhat similar relations are exposed in the hilly meadow opposite the Mountney farm, along the East Road (Pl. 5, point CL). Here a fine-grained and crenulate gray limestone passes into a coarse white marble toward the granite-syenite ridge which parallels the road on the north. This marble is undoubtedly continuous with that exposed at the intersection of the Clear Lake and East Roads, a few hundred yards to the east. At the latter locality nodular fragments of coarse white marble occur as inclusions in the lime mylonite.

There is no categorical reason why there may not have been a dozen alternating periods of milling and recrystallization. But most of the marble intrusion seems to have been accompanied and perhaps lubricated, by thin and highly fluid alkaline liquids, and in such an environment it is not likely that mylonization would be extensively developed. In fact, evidence of early mylonization could be preserved only by the absence of subsequent flowage, since extensive movement would almost surely destroy the transition between gray limestone and coarse white marble. The metamorphism which accompanied the intrusion of marble was for the most part an ordinary recrystallization. In the closing stages, perhaps after the solidification or escape of the magmatic lubricant, mylonization became the dominant mechanism of flow. This mylonization

persisted until confining pressures had been reduced to the point at which large-scale fractures in marble became possible, for the mylonite contains not only boulders of coarse marble but also, in rare instances, of lime mylonite itself. Judging by the composition of enclosures, the flowage of these marble bands must have occurred after the solidification of granite and syenite and during or before the injection of urtitic magma.

Most of the metamorphism of marble has been accomplished without extensive re-solution. Small quantities of calcite have passed into solution, however, and wherever the mineral is present in syenite it clearly cuts and replaces feldspar (Pl. 3, fig. 2). Only rarely is calcite of this type of any quantitative importance. A few patches of biotite marble exposed along the Clear Lake Road may have been formed by the more or less complete substitution of calcite for feldspar, as suggested by Bowen (1924) at Fen.

In short, where calcite appears to have crystallized from a liquid it is rarely more than a minor constituent, while the emplacement of those rocks which can justly be called carbonatite (intrusive *carbonate* rocks) has everywhere been accomplished without the intervention of a liquid of closely related composition. None of the carbonate in the area is truly magmatic, and the vast bulk is metamorphic rather than hydrothermal.

COMPARISONS WITH RELATED AREAS

Although no single area is exactly analogous to the Haliburton-Bancroft region, innumerable partial parallels are available. Space permits the discussion of only a few.

Laitakari's description of the Pargas amphibolites has already been mentioned. Concerning the generation of plagioclase-amphibole rocks by contact metamorphism of marble, he found himself forced to accept the same extreme position previously taken by Adams and Barlow. In the proper metamorphic environment the mineralogical and textural differences between gabbro, tuff, ash, and limestone or dolomite are lost, and the possibility of distinguishing between these very different rock types rests upon the chance survival of critical geological relationships. Laitakari's results are all the more surprising in the light of the sharp chemical differences between the two areas. Whereas the rocks and minerals of Pargas are conspicuously rich in lime, magnesia, and alumina, as opposed to iron oxides and alkalis, the converse is true of Bancroft.

The coarse white marble of the Bancroft alkaline complex may be compared to similar rocks described from Alnö by Högbom (1895), from Fen by Brögger (1924), from Sekukuniland by Shand (1921), and from Magnet Cove by Landes (1931). At Fen these carbonate rocks have

been considered igneous by Brögger and also by Tomkeieff (1938) chiefly because they form isolated bodies which cannot be seen to be continuous with sedimentary limestones. Geographical isolation was also the only "evidence" of an intrusive origin for the carbonatites of Alnö until Von Eckermann (1938) indicated that in this case the carbonate rocks form cone-sheets. In contrast to this the Bancroft carbonatites are visibly intrusive into surrounding rocks. There is no reason to doubt that these true intrusive marbles have been formed from the Grenville marble or that the Grenville marble is itself of sedimentary origin. The carbonatites of Fen have been assumed to be igneous even though they cannot be shown to be intrusive. The carbonatites of Bancroft are surely intrusive and are just as surely not igneous.

Prominent and useful as it is in determining age relations, the intrusive character of the Bancroft carbonatites is only incidental. Essentially they are enclosures isolated from the southern Grenville by the intrusion of alkaline rocks or granite. They differ only in size from the smaller marble enclosures of Sekukuniland, Magnet Cove, the Kaiserstuhl, the Monteregian Hills, and, ultimately, the ejected blocks of Vesuvius. In doubtful cases such as Alnö, Fen, or Jacupiranga, the burden of proof properly rests on those who suggest an igneous origin. If the rocks are igneous they must be either intrusive or extrusive. They are certainly not extrusive, and there is no reason even to suppose that they are igneous until they are shown to be intrusive in the ordinary geologic sense, rather than merely by their geographic isolation. As at Bancroft, it may be that, instead of proving an igneous origin, intrusive habit only masks a long metamorphic history of which it is the final expression.

Granulation of marble has been described from Troviken, Norway (Vogt, 1898), from Iona, Scotland (Coomaraswamy, 1903), from the famous "Lochseitenkalk" of the Alps (Heim, 1921), and from several localities in the Haliburton-Bancroft field (Adams and Barlow, 1910).

The lime mylonites of the Bancroft complex are of extraordinarily fine grain. They would probably be isotropic if composed of quartz or feldspar instead of calcite. No calcite remnants of the type described and pictured by Adams and Barlow (1910, p. 212) have been found, and uncrushed calcite occurs only in discrete marble breccia-fragments. The mylonites of the Bancroft area are also unusual in that they are actually separate intrusives, cutting or brecciating all other rocks save the foyaites.

Dixey, Campbell Smith, and Bisset (1937) have recently described a series of pipes cutting the basement complex in Chilwa, Nyassaland. These consist chiefly of breccia in which the fragments are syenite and the matrix carbonate. The carbonate may be either coarse and white or very fine-grained and dark. As at Bancroft, syenites are cut and

enclosed by carbonatite, but nepheline rocks cut the breccia and are never found as enclosures in it. The petrographic descriptions given are incomplete, and the further study planned has been delayed by the war. In his most recent published statement, Campbell Smith (1938) favored a magmatic origin for these carbonate rocks. But the available information suggests a remarkable analogy between the carbonatite of Chilwa and the flow marble and lime mylonite breccia of the Bancroft complex. As described by Osborne and Grimes-Graeme (1936), the St. Helen's Island breccia, in Montreal, may very well be another lime mylonite.

The similarity of the canadites and umptekites of Almunge and Bancroft has already been noted by Quensel (1914), whose comparison was based largely on the nepheline rocks, since the syenites and shonkinites of the Haliburton-Bancroft field were only briefly described by Adams and Barlow. With the more complete description of the saturated rocks presented in this paper the analogy becomes even more striking, extending now to minor and often inconsequential details. In both places there is the same transition between pink granite and syenite, though Quensel considers this transition the result of assimilation of granite by syenite. Quensel mentions that he is often unable to distinguish between granulated and aplitic syenites, and this is also true at Bancroft. As at Bancroft, perthite is the dominant and "often the only" feldspar of the syenites, while albite characterizes the nepheline rocks. (The feldspars of the syenites show the same varied colors as those of Bancroft, and as at Bancroft the albite of the nepheline rocks is white.) Quensel notes that "hastingsite" is more common in syenite than foyaite, the amphibole of the foyaites being more closely allied to riebeckite or arfvedsonite. All the "deep green hornblende" measurements in the Bancroft complex were made on ijolites or malignites, while only "hastingsite" values were obtained from the amphiboles of the syenite-shonkinite group.

In the hastingsite of Almunge, Quensel found that Z lay along the b axis and the crystals were length fast. This orientation has been reported in amphibole from the Haliburton-Bancroft field by Billings (1928). There is no limestone exposed in or near the Almunge complex, but vesuvianite is often present in the alkaline rocks. Quensel finds that syenite (umptekite) is younger than foyaite (canadite) but he holds that the alkaline rocks as a whole are younger than granite. In general, he favors the limestone-syntexis hypothesis although he feels that critical evidence is lacking.

The presence of very late highly sodic and acid pegmatites at Bancroft recalls Bowen's valuable discussion of "petrogeny's residua system" (Bowen, 1937). These late acid pegmatites invite comparison with the grorudite of the Christiania district (Brögger, 1894), the aegirine aplites

of Borolan (Shand, 1911), and similar rocks at Red Hill (Pirsson and Washington, 1907). These are dike rocks or pegmatites described in each case as younger than the principal alkaline intrusives. Insofar as plutonic rocks of granitic affinities are concerned, "petrogeny's residua system" is highly alkaline but also in many instances highly siliceous. This seems to apply even in areas in which large quantities of nepheline have been generated. The sharp localization of desilication, in both place and time, requires special explanation. In the Haliburton-Bancroft region the special explanation which places least strain upon the field facts is limestone-syntexis.

REFERENCES CITED

Adams, F. D., and Barlow, A. E. (1909) *The nepheline and associated alkaline syenites of eastern Ontario,* Royal Soc. Canada, Tr., 3d ser., vol. II, sec. iv, p. 3-76.

——— (1910) *Geology of the Haliburton and Bancroft areas, province of Ontario,* Geol. Survey Canada, Mem. 6, 419 pages.

Billings, M. P. (1928) *The mineralogy, optics, and chemistry of the hastingsite group,* Am. Mineral., vol. 13, p. 287.

Bowen, N. L. (1924) *The Fen area in Telemark, Norway,* Am. Jour. Sci., 5th ser., vol. 8, p. 1.

——— (1928) *Evolution of the igneous rocks,* Princeton Univ. Press, 334 pages.

——— (1937) *Recent research . . .,* Am. Jour. Sci., 5th ser., vol. 33, p. 13.

Brögger, W. C. (1894) *Die Eruptivgesteine des Kristianiagebietes,* vol. I. Videnskabssels Kabets Skrifter, I, Math.-Nat. Klasse, no. 4.

——— (1921) *Die Eruptivgesteine des Kristianiagebietes,* vol. IV.

Campbell Smith, W. (1938) *Alkali rocks associated with limestone of apparently intrusive nature,* Brit. Assoc. Adv. Sci., Pr., sec. C, p. 41.

Coomaraswamy, A. K. (1903) *Observations on the Tiree marble . . .,* Geol. Soc. London, Jour., vol. LIX, p. 91.

Daly, R. A. (1910) *Origin of the alkaline rocks,* Geol. Soc. Am., Bull., vol. 21, p. 87.

——— (1914) *Igneous rocks and their origin,* McGraw-Hill Co., p. 429.

——— (1918) *Genesis of the alkaline rocks,* Jour. Geol., vol. 26, p. 97.

——— (1933) *Igneous rocks and the depths of the earth,* McGraw-Hill Co., p. 502.

Dixey, F., Campbell Smith, W., and Bisset, C. R. (1937) *The Chilwa series of southern Nyassaland,* Geol. Survey Dept. Nyassaland Protectorate, Bull. 5, 185 pages.

Ellsworth, H. V. (1922) *Radium-bearing pegmatites of Ontario,* Geol. Survey Canada, Summ. Rept. 1921, pt. D, p. 51-70.

Foye, W. G. (1915) *Nephelite-syenites of Haliburton County, Ontario,* Am. Jour. Sci., 4th series, vol. 40, p. 413.

Goldich, S. S., and Kinzer, H. H. (1939) *Perthites from Tory Hill, Ontario,* Am. Mineral., vol. 24, p. 407.

Goudge, M. E. (1938) *Limestones of Canada,* Canada Dept. Mines, Mines Branch, Mem. 781, Part IV, Ontario, 196 pages.

Heim, A. (1921) *Geologie der Schweiz,* vol. 2.1, p. 94.

Högbom, A. (1895) *Das Nephelinsyenite Gebiet auf der Insel Alnö,* Geol. Förhand., Förein., Stockholm, vol. 17, 102 pages.

Holmes, A. (1937) *Petrology of the volcanic area of Bufumbira,* Geol. Surv. Uganda, Mem. III, pt. II, p. 100.

Hurley, P. M., and Goodman, C. (1941) *Helium retention in common rock minerals,* Geol. Soc. Am., Bull., vol. 52, p. 545.

Keith, A. (1939) *Petrology of the alkaline intrusive at Blue Mountain, Ontario,* Geol. Soc. Am., Bull., vol. 50, p. 1795.

Laitakari, A. (1921) *Uber die Petrographie und Mineralogie der Kalksteinlagerstätten von Parainen (Pargas),* Bull. 54, Comm. Géol. de Finlande, 113 pages.

Landes, K. K. (1931) *A paragenetic classification of the Magnet Cove minerals,* Am. Mineral., vol. 16, p. 313.

Osborne, F. F. (1930) The *nepheline-gneiss complex near Egan Chute, Dungannon Township, etc.,* Am. Jour. Sci., 5th ser., vol. 20, p. 33.

——— and Grimes-Graeme, R. (1936) *The breccia on St. Helen Island, Montreal,* Am. Jour. Sci., 5th ser., vol. 32, p. 43.

Pirsson, L. V., and Washington, H. S. (1907) *Contributions to the geology of New Hampshire, No. 3, On Red Hill, Moultonboro,* Am. Jour. Sci., 4th ser., vol. 23, p. 433.

Quensel, P. (1914) *The alkaline rocks of Almunge,* Geol. Inst. Upsala, Bull., vol. XII, 200 pages.

Shand, S. J. (1910) *On borolanite and its associates in Assynt,* Edinburgh Geol. Soc., Tr., vol. 5, pt. IX, p. 396.

——— (1921) *The nepheline rocks of Sekukuniland,* Geol. Soc. S. Africa, Tr., vol. XXIV, p. 111.

——— (1927) *Eruptive rocks,* Murby & Co., 360 pages.

Smyth, C. H. (1913) *The chemical composition of the alakaline rocks . . .,* Am., Jour. Sci., 4th ser., vol. 36, p. 33.

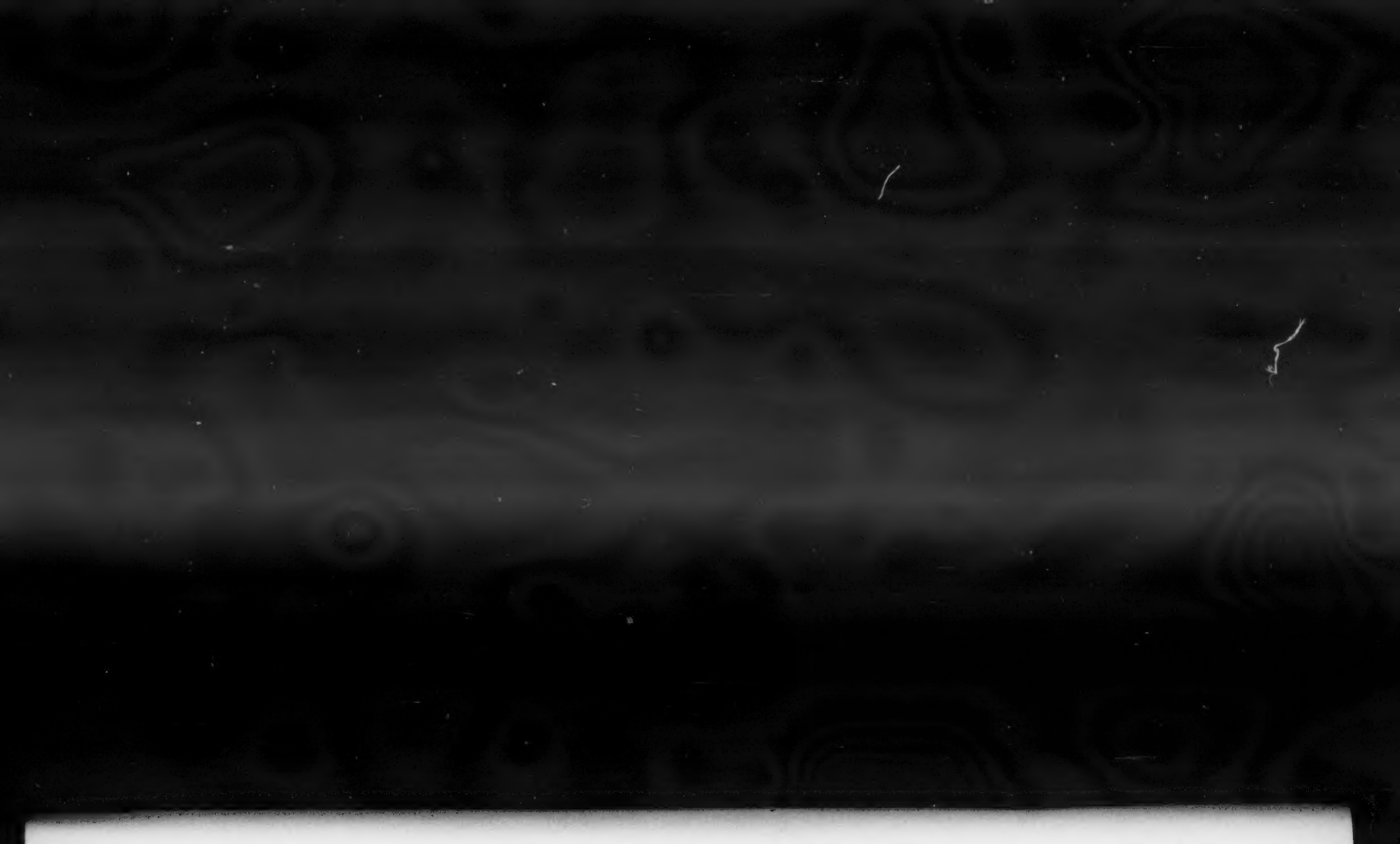
Tomkeieff, S. I. (1938) *The role of carbon dioxide in igneous magma,* Brit. Assoc. Adv. Sci., Pr., sec. C, p. 41.

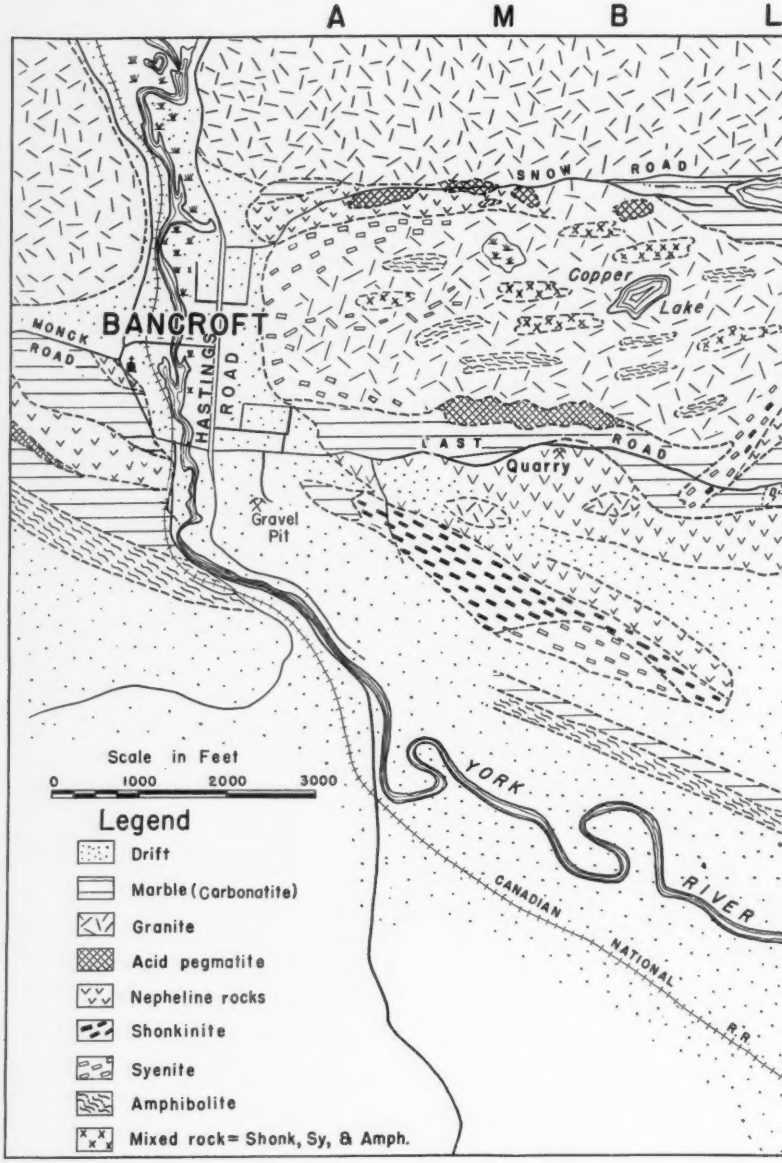
Vogt, J. H. L. (1898) *Die Marmor in Bezug auf Seine Geologie, Struktur, u.s.w.,* Zeitschr. Prakt. Geol., vol. 6, p. 5.

Von Eckermann, H. (1938) *Origin of carbonate rocks associated with alkali-rich intrusives,* Brit. Assoc. Adv. Sci., Pr., sec. C, p. 40.

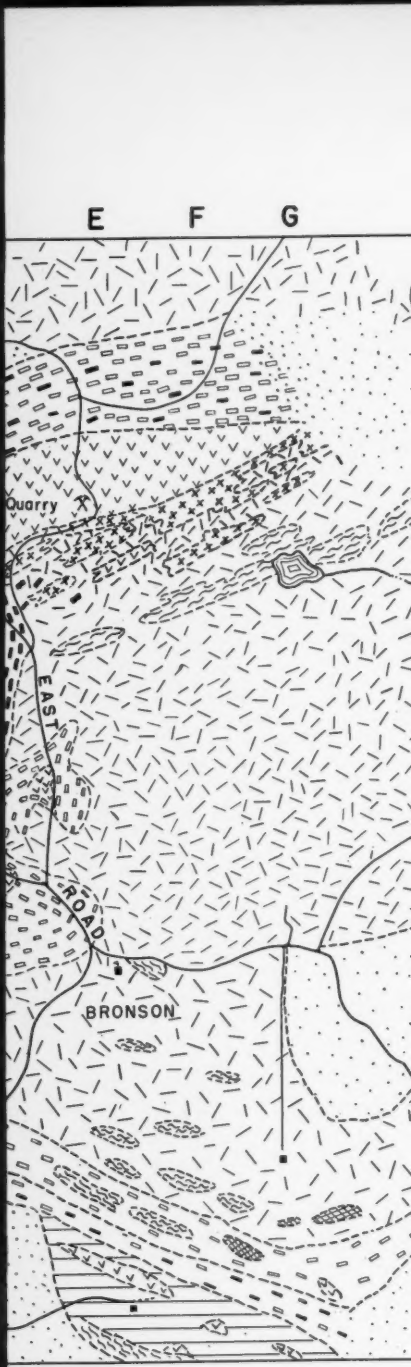
Wegmann, C. E. (1935) *Zur Deutung der Migmatite,* Geol. Rundschau, vol. 26, p. 305.

Manuscript received by the Secretary of the Society, May 26, 1941.
Read before the Geological Society, December 30, 1939.




A M B L
SNOW ROAD
Copper Lake
BANCROFT
MONCK ROAD
HASTINGS ROAD
EAST ROAD
Quarry
Gravel Pit
YORK RIVER
CANADIAN NATIONAL R.R.
Scale in Feet
0 1000 2000 3000
Legend
Drift
Marble (Carbonatite)
Granite
Acid pegmatite
Nepheline rocks
Shonkinite
Syenite
Amphibolite
Mixed rock= Shonk, Sy, & Amph.

GEOLOGIC MAP OF BANCROFT AREA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ROAD
BRONSON

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Scattered outcrops
of Nepheline pegmatite